Transforming the DoD Test and Evaluation Enterprise to Enable Unmanned Autonomous Systems of Systems

by

Karl K. Cowart

B.S. Mechanical Engineering, Louisiana State University, 1998
M.S. Aerospace Engineering, Georgia Institute of Technology, 2000

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology
January 2011
[February 2011]

Signature of Author ______________________________
Karl K. Cowart
System Design and Management Program
21 January 2011

Certified by ______________________________
Ricardo Valerdi
Thesis Supervisor
Research Associate, Engineering Systems Division

Read by ______________________________
Deborah J. Nightingale
Thesis Reader
Professor of the Practice of Aeronautics and Astronautics and Engineering Systems

Certified by ______________________________
Patrick Hale
Director
System Design and Management Program

Disclaimer -- The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

(THIS PAGE INTENTIONALLY LEFT BLANK)

Transforming the DoD Test and Evaluation Enterprise to Enable Unmanned Autonomous Systems of Systems

by

Karl K. Cowart

Submitted to the System Design and Management Program
on January 21, 2011 in partial fulfillment of the requirements for the Degree of
Master of Science in Engineering and Management

Abstract

Many US Department of Defense (DoD) systems operate within a systems of systems construct, which present many challenges and will be ever increasing for test and evaluation of unmanned autonomous systems of systems. Challenges include emergent behaviors along with resource limitations that will cause test planners to balance tradeoffs in order to effectively plan test missions. The current test and evaluation enterprise will have to change in order to address such challenges.

This thesis investigates how a decision support system can be utilized by DoD test and evaluation stakeholders to adequately plan missions for unmanned autonomous systems of systems testing. Research was conducted to serve dual strategic and tactical purposes. Strategically, this research served to identify potential gaps in the test and evaluation enterprise, which create challenges for unmanned autonomous systems of systems testing. Tactically, this research investigated how a decision support system can deliver value to the stakeholders of the enterprise.

This effort was guided by five research focus areas. First, focus was on differentiating testing at the system and systems of systems levels. Second, test and evaluation stakeholders were identified and their saliency was determined. Third, stakeholder values for testing of unmanned systems were gathered via stakeholder interviews. Fourth, challenges of testing unmanned autonomous systems of systems were determined. Lastly, a use case example was utilized to demonstrate how stakeholder value is generated by the use of a decision support system.

Thesis Supervisor: Ricardo Valerdi
Title: Research Assistant, Engineering Systems Division

Thesis Reader: Deborah J. Nightingale
Title: Professor of Practice of Aeronautics and Astronautics and Engineering Systems

(THIS PAGE INTENTIONALLY LEFT BLANK)

Table of Contents

ABSTRACT 3
TABLE OF CONTENTS 5
LIST OF FIGURES 9
LIST OF TABLES 11
BIOGRAPHICAL NOTE 12
ACKNOWLEDGMENTS 13
EXECUTIVE SUMMARY 15
CHAPTER 1 – INTRODUCTION 17
  1.0 – OPENING REMARKS 17
  1.1 – RESEARCH MOTIVATIONS 17
  1.2 – THESIS TOPIC AND RESEARCH QUESTIONS 20
  1.3 – THESIS ROADMAP 22
CHAPTER 2 – LITERATURE REVIEW 23
  2.0 – OPENING REMARKS 23
  2.1 – UNMANNED SYSTEMS AND FUTURE OPERATIONS 24
  2.1.1 – CURRENT UNMANNED SYSTEMS 24
  2.1.2 – FUTURE OF UNMANNED SYSTEMS 27
  2.2 – DEFENSE ACQUISITION 31
  2.3 – A SYSTEM AND SYSTEMS OF SYSTEMS 33
  2.3.1 – SYSTEMS 33
  2.3.2 – SYSTEMS-OF-SYSTEMS – DEFINITIONS AND CHARACTERISTICS 34
  2.4 – TEST AND EVALUATION IN THE DOD ACQUISITION PROCESS 37
  2.4.1 – TEST AND EVALUATION DESCRIPTION 37
  2.4.2 – REDUCING RISKS THROUGH TEST AND EVALUATION 38
  2.4.3 – DEFINITION OF DEVELOPMENTAL TEST AND EVALUATION 38
  2.4.4 – DEFINITION OF OPERATIONAL TEST AND EVALUATION 38
  2.4.5 – IDEALS OF TEST AND EVALUATION 39
  2.5 – SYSTEM T&E VERSUS SYSTEMS OF SYSTEMS T&E 39
  2.6 – DECISION SUPPORT SYSTEMS 40
  2.7 – VALUE AND ENTERPRISE TRANSFORMATION 41

2.8 – Enterprise Architecture 46
2.9 – Stakeholders and Saliency 48
2.10 – Chapter Summary 52

CHAPTER 3 – T&E SOS STAKEHOLDER ANALYSIS 55

3.0 – Opening Remarks 55
3.1 – Enterprise Description 55
3.2 – Stakeholder Identification 58
3.3 – Stakeholder Saliency 60
3.4 – Stakeholder Interview Results 61
3.5 – Stakeholder Interview Validity 69
3.6 – Chapter Summary 70

CHAPTER 4 – "AS-IS" ENTERPRISE ARCHITECTURE ANALYSIS OF T&E SOS 73

4.0 – Opening Remarks 73
4.1 – Service and Product Views 73
4.2 – Organization View 74
4.3 – Policy and Strategy Views 78
4.4 – The Process View Explained 80
4.5 – Knowledge and Information Views 84
4.6 – Chapter Summary 85

CHAPTER 5 – EMPLOYING A DSS TO ENABLE T&E ENTERPRISE UASOS PLANNING 87

5.0 – Opening Remarks 87
5.1 – DSS Frameworks 87
5.2 – DSS Process Flow 88
5.3 – DSS Design Considerations 90
5.4 – DSS "State-of-the-Practice" 92
5.4.1 – Basic DSS Classifications 93
5.4.2 – Examples of DSS Utilization 93
5.4.3 – Important DSS Capabilities for *PATFrame* 95
5.5 – Experiments, Quasi-experiments and Case Studies 95
5.6 – Evaluating a UASoS Test Planning Tool 96
5.7 – *PATFrame* Use Case Example 97
5.7.1 – Use Case Description 97
5.7.2 – Examining the Utility of the SoS Upgrades 101
5.7.3 – Examining the Quality Risk of the SoS Upgrades 103

5.7.4 – Testing Cost 105
5.7.5 – Putting It All Together 105
5.8 – Chapter Summary 105

CHAPTER 6 – CONCLUSIONS AND FUTURE RESEARCH 107
6.0 – Opening Remarks 107
6.1 – Conclusions 107
6.2 – Future Value Considerations for UASoS Test and Evaluation 109
6.3 – Next Steps 111

BIBLIOGRAPHY 113
APPENDIX A – TECHNICAL DESCRIPTION FOR *PATFRAME* (VALERDI ET AL. 2008) 123
APPENDIX B – COUHES FORM 129
APPENDIX C – STAKEHOLDER INTERVIEW FRAMEWORK 131
APPENDIX D – STAKEHOLDER LEGITIMACY FACTORS 133
APPENDIX E – SYSTEMS VS SYSTEMS OF SYSTEMS (SAUSER 2006) 137
APPENDIX F – ACRONYMS 139

(THIS PAGE INTENTIONALLY LEFT BLANK)

List of Figures

Figure 1 – SoS Hierarchy Diagram 18

Figure 2 – Literature Review Topics 24

Figure 3 – Unmanned Aerospace Vehicle Spectrums of Designs (Dunaway 2008) 27

Figure 4 – The Three Aspects of ALFUS (Huang et al. 2007) 28

Figure 5 – CAC Rating Scale for UMS (Huang et al. 2007) 31

Figure 6 – Defense Acquisition Process (DoD 2008) 32

Figure 7 – Value Creation Iterates and Adapts (Murman et al. 2002) 42

Figure 8 – Eight View Enterprise Architecture Framework (Nightingale 2009) 48

Figure 9 – Generic Enterprise Stakeholders (Nightingale & Srinivasan 2011) 49

Figure 10 – Stakeholder Typology: One, Two or Three Attributes Present (Mitchell, Agle and Wood 1997) 51

Figure 11 – Systems of Systems Test and Evaluation Stakeholder Water Drop Model 56

Figure 12 – US Air Force Intelligence, Surveillance and Reconnaissance Systems of Systems (Maddocks 2010) 57

Figure 13 – Stakeholder Value for Operational Testers 62

Figure 14 – Stakeholder Value for Developmental Testers 64

Figure 15 – Stakeholder Value for Contractor Program Managers 65

Figure 16 – Stakeholder Value for Government Program Managers 66

Figure 17 – Stakeholder Value for Systems Engineers 67

Figure 18 – Stakeholder Value for Acquisition Level Stakeholders 68

Figure 19 – Department of Defense Test and Evaluation Enterprise 75

Figure 20 – US Air Force Materiel Command Operating Locations (AFMC Services 2010) 77

Figure 21 – US Air Force Operational Test and Evaluation Center Locations (AFCEA 2010) 78

Figure 22 – Strategy for Early Influence (Maddocks 2010) 79

Figure 23 – System Integrated DT / OT Process for MS B to MS C 81

Figure 24 – Decision Process Flow Chart (Aronson et al. 2007) 89

Figure 25 – Test and Evaluation Decision Process Flow Chart 90

Figure 26 – Overall *PATFrame* Workflow 97

Figure 27 – Use Case Scenario Description (Kenley & Cowart 2010) 98

Figure 28 – Overhead Picture of Use Case Scenario Description (Kenley & Cowart 2010) 99

Figure 29 – Stakeholder Functions for Value-Based Testing (Kenley & Cowart 2010) 99

Figure 30 – Value Based Testing Use Case Model Diagram (Kenley & Cowart 2010) 100

Figure 31 – Prescribed System of Systems Environments 124

Figure 32 – Adaptive Architectural Framework 126

(THIS PAGE INTENTIONALLY LEFT BLANK)

List of Tables

TABLE 1 – FY2009-2013 PRESIDENT'S BUDGET FOR UNMANNED SYSTEMS (OUSD(AT&L) 2009A) 26
TABLE 2 – DOD UNMANNED SYSTEMS DEVELOPMENT GOALS (OUSD(AT&L) 2009A) 26
TABLE 3 – SOFTWARE IN DOD SYSTEMS (COYLE 2010) 34
TABLE 4 – SYSTEMS VS SYSTEMS OF SYSTEMS (SAUSER & BOARDMAN 2006) 35
TABLE 5 – SYSTEMS VS SYSTEMS OF SYSTEMS (ODUSD(A&T) 2008) 37
TABLE 6 – SOS TEST AND EVALUATION CHALLENGES (DAHMAN ET AL. 2010) 40
TABLE 7 – VALUE DEFINITIONS [ADOPTED FROM (BURGESS 2010)] 43
TABLE 8 – ENTERPRISE TRANSFORMATION PRINCIPLES (NIGHTINGALE & SRINIVASAN 2011) 43
TABLE 9 – ENTERPRISE ARCHITECTURE VIEWS (NIGHTINGALE 2009) 48
TABLE 10 – COMMON STAKEHOLDER GROUPS (NIGHTINGALE & SRINIVASAN 2011) 50
TABLE 11 – TEST AND EVALUATION ENTERPRISE STAKEHOLDER REPRESENTATIVES 58
TABLE 12 – STAKEHOLDER SALIENCY INDEX 61
TABLE 13 – SUMMARY OF IMPORTANT STAKEHOLDER VALUES 71
TABLE 14 – DECISION SUPPORT FRAMEWORKS (GORRY AND SCOTT-MORTON 1971) 88
TABLE 15 – OVERCOMING ACKNOWLEDGED SOS T&E CHALLENGES 92
TABLE 16 – USE CASE MODEL ENTRIES FOR "UTILITY ATTRIBUTES INDEX" 102
TABLE 17 – USE CASE RISK FACTORS 103
TABLE 18 – USE CASE WEIGHTS FOR QUALITY RISK FACTORS 104
TABLE 19 – USE CASE RELATIVE DEGREE OF RISK FACTORS 104
TABLE 20 – USE CASE FUNCTION TEST COST IMPORTANCE 105
TABLE 21 – STAKEHOLDER POWER FACTOR DETERMINATION (GROSSI 2003) 133
TABLE 22 – STAKEHOLDER CRITICALITY FACTOR DETERMINATION (GROSSI 2003) 134
TABLE 23 – STAKEHOLDER LEGITIMACY FACTOR DETERMINATION (GROSSI 2003) 135

Biographical Note

Karl Kristopher Cowart is a Major in the United States Air Force. He was born and raised in Baton Rouge, Louisiana having graduated from Scotlandville Magnet High School. He went on to graduate from Louisiana State University in 1998 with a B.S. in Mechanical Engineering, and was commissioned as an officer in the USAF Acquisitions Career Field. In 2000, he graduated from the Georgia Institute of Technology with a M.S. in Aerospace Engineering. From 2000 to 2002, he served as a structural loads engineer at the Air Force SEEK EAGLE Office at Eglin AFB, FL conducting store compatibility analysis and flight testing on A-10, F-15, F-16, and B-2 aircraft. In 2003, he graduated from the Experimental Flight Test Engineering Course at the USAF Test Pilot School at Edwards AFB, CA. From 2004 to 2005, he was a Test Conductor/Test Director on the USAF F-22 Raptor. In this capacity, he planned and executed high risk F-22 envelope expansion test missions clearing the Raptor's flight envelope providing the aircraft's superior combat agility. From 2005 to 2009, he served at Hanscom AFB, MA developing battle management, command and control systems.

He is married to the former Nicole Claudette Bayard, and they have a beautiful three year old daughter, Elizabeth Madeline.

Acknowledgments

There are many that I want to thank in supporting my efforts in pursuing this research. The year leading up to my opportunity to attend MIT was riddled with medical issues that required major surgery causing a delay my start date.

These challenges were overcome and my surgery was successful, therefore the first accolades go to God, who has answered my prayers of allowing me to overcome these challenges in order to accomplish a lifelong dream of attending MIT.

I want to thank the United States Air Force for selecting me to attend MIT and allowing me to start the program out of cycle as a result of my health condition. In return to the Air Force, I will be dedicated to the giving back the value that I have gained from this experience.

I want to thank Dr Ricardo Valerdi and Professor Deborah Nightingale for their guidance and support in my completion of this thesis. Your encouragement and motivation encouraged me to overcome any self doubts and challenges I faced during this research effort.

Special thanks go to the people that allowed me the time to conduct interviews in support of this research effort. The data provided enabled this effort to be a success.

I wish to thank Mr Pat Hale and the members of the MIT System Design and Management staff for their assistance in navigating the SDM curriculum and making it possible for me to complete the program in 13 months.

Thanks goes out to the members of the SDM 10 cohort as well as my Lean Advancement Initiative associates for their friendships and the lasting memories. I will endeavor to maintain contact with you as time goes on. I might even breakdown and join Facebook.

Lastly, I want to thank my wife for being so supportive of my pursuit of another degree. You have carried a large load the last couple of years in having to nurse me back to health as well as spend very long hours taking care of our most beautiful creation. Our little girl, Lizzie! My love and this thesis are for the both of you.

(THIS PAGE INTENTIONALLY LEFT BLANK)

Executive Summary

Many US Department of Defense (DoD) systems operate within a systems of systems (SoS) construct, which present many challenges and will ever increase for test and evaluation of unmanned autonomous systems of systems. Challenges include emergent behaviors along with resource limitations that will cause test planners to balance tradeoffs in order to effectively plan test missions. The current test and evaluation enterprise will have to change in order to address such challenges.

This thesis investigates how a decision support system can be utilized by DoD test and evaluation stakeholders to prescriptively plan missions for unmanned autonomous systems of systems testing. Research was conducted to serve dual strategic and tactical purposes. Strategically, this research served to identify potential gaps in the test and evaluation enterprise, which create challenges for unmanned autonomous systems of systems testing. Tactically, this research investigated how a decision support system can deliver value to the stakeholder of the enterprise.

This effort was guided by several research focus areas. First, focus was on differentiating testing at the system and systems of systems levels. Research found that testing at the system level is typically achievable granted the system requirements are well understood and adequate resources are available to complete testing. Systems of systems test and evaluation is more of a challenge than system testing due to the difficulty of synchronizing across multiple systems' life cycles; given the complexity of all the moving parts and potential for unintended consequences.

Second, systems of systems test stakeholders were identified and their saliency was determined. The identified stakeholders are represented by external and internal groups. The external stakeholders are considered to be Taxpayers, Congress, Acquisition Level, End Users and representatives from the Joint Interoperability Test Command. The internal stakeholders are considered to be Program Managers, Systems Engineers, Developmental Testers and Operational Testers. Saliency of the stakeholders was determined in order to determine who has the most impact on the T&E of a SoS from the perspectives of power, legitimacy and urgency and it was determined that the internal stakeholders have the most impact on the outcome of T&E because they are in direct contact with the constituent systems of the SoS that is undergoing test.

Third, an analysis was conducted in order to determine the stakeholder values and expectations for testing of unmanned systems along with how the current T&E enterprise performs in satisfying those expectations. Results of the survey found the current enterprise construct does not satisfactorily meet expectations of the stakeholders. For example, constituent systems undergoing development testing (DT) can fail to verify all constituent system requirements prior to operational testing (OT) at the SoS level, which can lead to schedule delays and cost increases. Another example is a lack of clear understanding of test boundaries between the constituent systems within the SoS, which can lead to confusion of ownership responsibility in the case of a failure at the SoS level.

Fourth, challenges of testing unmanned autonomous systems of systems were determined based on stakeholder interviews. Stakeholders pointed out the following challenges: ensuring smooth transition from DT to OT for constituent members of the SoS; not having the ability to predict potential for emergent behaviors (both good and bad) and be able to test these emergent behaviors within available resources; being able to build the constituent systems to design specifications and understand the required SoS interfaces; being able to scope and understand test risks and development of risk mitigation plans; building and establishing continued trust amongst SoS team members; and ensuring stability of SoS requirements in order to not extend required time for testing.

Lastly, research was conducted in order to show how a decision support system (DSS) can be utilized in order to deliver value to the T&E enterprise for the testing of unmanned autonomous systems of system. It was determined that a DSS can be utilized and add value in overcoming SoS T&E challenges such as measuring the performance of a SoS in preparation for an acquisition decision; aligning asynchronous schedules within a SoS; identifying emergent behaviors as well as developing risk mitigation plans; and assist in understanding how a SoS will potentially perform in the test environment. Also, a value based testing use case was shown in order to demonstrate the merits of utilizing a DSS for unmanned autonomous systems of systems testing that showed how test priorities can be determined based on the SoS functionality being tested; risk considerations; and cost determination.

Chapter 1 – Introduction

1.0 – Opening Remarks

Unmanned systems "allow us to dominate the battle space we never thought we would be able to dominate" (Hawkins 2010). This quote from Major General Jim Myles, commander of the Aviation and Missile Command and Redstone Arsenal, sheds light on the value that unmanned systems provide the US Department of Defense (DoD). The unmanned systems arena has seen a tremendous amount of growth and is destined to grow even more in the future. Military operations in Afghanistan and Iraq are prime examples of the development and utilization of unmanned systems where there are currently more than 7,000 drones are currently deployed (Hennigan 2010).

1.1 – Research Motivations

The Fiscal Year 2009-2034 Unmanned Systems Integrated Roadmap (USIR) affirms that unmanned systems are highly desired by Combatant Commanders and have made key contributions to the current operations in Iraq and Afghanistan (OUSD(AT&L) 2009). Also, the USIR points out the significant number of missions that unmanned systems have conducted as of Oct 2008: approximately 500,000 hrs have been flown by unmanned aircraft systems; approximately 30,000 missions have been conducted by unmanned ground systems in order to detect/neutralize over 15,000 improvised explosive devices; and unmanned maritime systems provided security to local ports.

The USIR is a strategically focused document that identifies the vision of the future for the DoD's plan for unmanned systems. It shows that $18.9 billion is allocated in the FY 2009-13 Presidential Budget for unmanned systems and provides seven goals in order to focus the DoD on delivering unmanned capabilities. One of these goals is to ensure test capabilities support the fielding of unmanned systems that are effective, suitable and survivable.

Future unmanned systems will be autonomous and will operate within a system of systems hereafter referred to as unmanned autonomous systems of systems (UASoS). Current unmanned systems are systems that are not occupied by human operators with an example being an Air Force Global Hawk (USAF 2009). Autonomous calls for a system to be cognizant of its surroundings, make decisions and react based on the inputs it perceives. This attribute will be an important focus area for future operations and will be relevant in all domains of military operations, which includes air, land, sea (surface and sub-surface) and space. As the DoD acquires future UASoS, the test and evaluation (T&E) of these systems will require complex and robust methods for verifying and validating that the systems can operate independently as well as be able to interface with the other systems that comprise the SoS, as depicted in Figure 1. This diagram represents a hierarchy for the SoS construct and consists of similar or disparate "systems" that interface with one another. Each individual system has subsystems that represent its internal functionality.

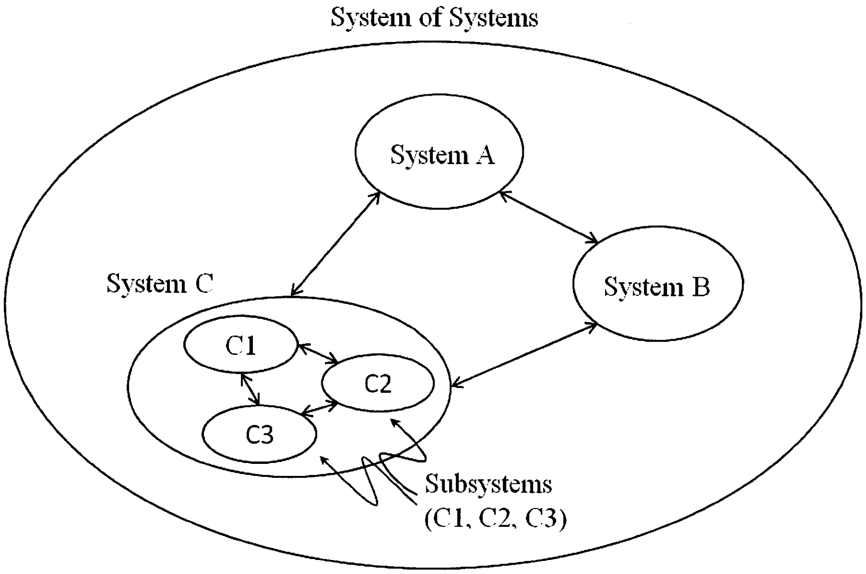


Figure 1 – SoS Hierarchy Diagram

In order to expand on the notion of requiring complex and robust T&E, consider testing in an acknowledged SoS framework versus that of a single system. An acknowledged SoS has recognized objectives, a designated manager, and resources for the SoS, and in which individual systems within the SoS retain independent ownership, objectives, funding, development and sustainment approaches (ODUSD(A&T) 2008). Professional testers are very proficient in testing single systems whereas Dahman et al. have identified seven T&E implications for acknowledged systems of systems (2010). These include (1) SoS validation criteria are more difficult to establish; (2) SoS conditions cannot be explicitly imposed on individual system T&E; (3) no clear analogs between SoS level objectives and those of the individual systems; (4) acquisition decisions are based on individual system as well as SoS level testing; (5) asynchronous individual system schedules make it difficult for SoS testing events; (6) SoS require more test points for detecting emergent behaviors; and (7) SoS increases subjectivity in assessing behavior as well as presenting challenges to aligning the systems.

Autonomy is also an important factor for future test and evaluation of UASoS. Autonomous systems introduce an additional level of complexity because the performance of unmanned systems in scenarios that are not anticipated is not very well understood not only at the system level, but also at the SoS level. This is similar to the practice of envelope expansion in flight testing of a new aerospace system. Envelope expansion is the practice of flying at different altitude and airspeed combinations in a conservative way via a build up approach in order to demonstrate the ability of the system by increasing dynamic pressure. In a similar way, unmanned systems testing will have to follow a build up approach in order to clear the envelope of potential risks due to emergent behaviors. Unmanned aerospace vehicle access to the US National Air Space is also a good example, which could lead to potential undesired emergent behaviors within in a UASoS framework (Hughes 2007).

Systems that are undergoing test and evaluation today do not necessarily get tested in the systems of systems framework until after developmental testing (DT) is near completion and they are about to enter the operational test (OT) phase. This is a limitation that can be overcome in the future, by the T&E enterprise's integration of DT and OT to streamline the overall testing requirements of the systems of systems (Sargeant 2010). This is important because the late identification of undesired emergent behavior, especially during OT, drives very costly, undesired redesign work.

Also, there will be limitations on the amount of T&E that can be completed due to time, money and resource constraints. The test community needs an effective approach to test planning that enables them to construct a test plan that optimizes measures of the level of verification and validation of the UASoS that can be achieved within the identified resource constraints.

The aforementioned aspects of UASoS T&E such as the implications for acknowledged SoS; autonomy; DT/OT integration and resource limitations are all aspects that identify a future T&E planning gap. In order to bridge this gap, a T&E Decision Support System (DSS) is being developed that will demonstrate the ability to effectively plan missions for test and evaluation of a UASoS to verify and validate that mission objectives can be accomplished. This planning tool is the ***P****rescriptive* ***A****daptive* ***T****est* ***Frame****work* (*PATFrame*) that is intended to aid testers in planning UASoS test missions in order to determine the possible existence of undesired emergent behaviors as well as prioritizing the sequence of missions based on limited test resources (time, funding, range availability and test assets) (Hess & Valerdi 2010).

1.2 – Thesis Topic and Research Questions

Test planning can be thought of from three distinct approaches: *normative, descriptive and prescriptive* (Hess & Valerdi 2010).

Normative decision analysis is often called rational decision analysis or axiomatic decision analysis (Sage 1992). Sage adds further clarity by stating that, in formal approaches, a set of *axioms* that a rational person would surely agree with is postulated, which leads to the *normative* (most desirable or optimum) behavior a decision maker should seek to follow. As taken from the definition, the normative approach sets an approach into how test and evaluation should be completed. As is pertains to DoD test and evaluation, normative T&E is stipulated through standards and instructions that state what needs to be accomplished in order for a system or capability to be adequately tested.

Descriptive, or behavioral, decision assessment is concerned with the way in which human beings in real situations actual make decisions (Sage 1992). Further, *way* includes both the process used to make a decision as well as the actual decision that was made." The definition of descriptive links the way something is accomplished to an actual experience. In DoD test and evaluation, this would apply to how an actual test mission is planned or takes place, which might not be the specific normative way of planning test missions.

Prescriptive decision assessment involves suggestions of appropriate decision behavior that tempers the formal normative approaches to insure that that the process reflects the needs of the real people in real decision situation (Sage 1992). Prescriptive is meant to provide direction in order to apply a correction caused by a deviation. This is the third approach to test and evaluation and can be characterized as the corrective action that can be taken in order to close between the descriptive and normative approaches of test and evaluation.

It is assumed this will stand to be the case for systems of systems testing of unmanned autonomous systems and will pose challenges to the planning of future test missions. Therefore, a methodology for the test planning of unmanned autonomous systems of systems needs to be developed in order for stakeholders in the DoD Test and Evaluation enterprise to obtain their maximum value from these types of missions.

The purpose of this thesis is to investigate how a decision support system can enable DoD test and evaluation stakeholders to adequately plan test missions for unmanned autonomous systems that will operate in a systems of systems environment. In order to address this topic, research was conducted to serve dual strategic and tactical purposes. Strategically, this research served to identify potential gaps in the US Department of Defense Test and Evaluation Enterprise that exist in order to handle unmanned autonomous systems of systems (UASoS). Tactically, this research investigated how a decision support system (DSS) can enable testers to more effectively plan (UASoS) test missions and deliver the expected value to the stakeholders.

In order to conduct the strategic investigation of this study, the following research questions were answered by analyzing the DoD Test and Evaluation enterprise from an Air Force perspective:

- How is test and evaluation from a system perspective different than that of systems of systems?
- Who are the primary stakeholders of the test and evaluation enterprise?
- What are primary stakeholder values towards unmanned autonomous systems of systems testing?
- What are primary challenges to UASoS test and evaluation?

At the tactical level, this thesis focused on how a decision support system (DSS) called *PATFrame* (Prescriptive Adaptive Test Framework) can be used in order to deliver the expected value of the test and evaluation enterprise stakeholders. In order to conduct this tactical level analysis, DSS design characteristics were examined in order to find a relation of how DSS could be utilized for T&E planning. Also, a "state of the practice" survey was conducted where several DSS that are being utilized by Defense and industry were examined in order to gain insight into how DSS are utilized. Lastly, practices for measures of performance were reviewed in order to show the verification / validation process of a DSS is performed. These research steps were conducted in order to answer the following tactical level research question.

- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

1.3 – Thesis Roadmap

Chapter 1 of this thesis provides the introduction material that motivated this research effort along with the research questions. Chapter 2 is a Literature Review that covers the information areas that are relevant to the material in this document, which include: unmanned systems; DoD acquisitions; requirements development; systems and systems of systems; test and evaluation of systems and systems of systems; decision support systems; value delivery; enterprise transformation; and enterprise stakeholder theory. Chapter 3 dives into the UASoS T&E the stakeholder analysis where the T&E stakeholders are identified for an Acknowledged SoS; stakeholder saliency is established; and interview results are presented in order to identify stakeholder values. Chapter 4 is an Enterprise Architecture analysis of the "As-Is" T&E enterprise through the strategy, service, process, policy, purpose, organization, knowledge and information lenses in order to examine potential UASoS T&E challenges within the current enterprise. Chapter 5 focuses on how a decision support system can be used by the UASoS T&E enterprise in order to deliver value to the stakeholder by: examining DSS design characteristics; process flow and measures of performance criteria. Chapter 6 sums up the findings to the research questions and explores how long term value can be delivered to the T&E enterprise along with next steps for this research effort.

Chapter 2 – Literature Review

2.0 – Opening Remarks

This chapter focuses on the literature review that was conducted in order to set the stage for addressing the research questions posed in Chapter 1. Figure 2 depicts a pictorial representation of the applicable material and how it is linked together. The first topic reviewed was unmanned systems in order to gain a perspective into how they are used today and provide insight into how they may be utilized in the future. Second, the DoD acquisition process was reviewed in order to provide a context of how systems are acquired, which included a review how requirements are generated using the Joint Capability Integration and Development System (JCIDS); how systems are acquired via the Acquisition System; and the test and evaluation process . Third, information was reviewed that compared a system to a systems of systems in order to provide an understanding of the complexities associated with test and evaluation of an SoS compared to traditional systems T&E. Fourth, Decision Support Systems (DSS) were reviewed in order to provide relevant insight into the use of these tools for UASoS test planning.

Further, relevant academic material associated with Enterprise Architecture and Integrating the Lean Enterprise is reviewed in order to understand stakeholder value delivery of *PATFrame* to the T&E enterprise. Enterprise Architecture is a framework that covers topics in architecting holistic and highly networked enterprise structures including: organizational structure; business models; organizational culture/behavior; enterprise architecture frameworks and standards; policy and process infrastructure; information technologies; and knowledge management. Integrating the Lean Enterprise addresses some of the important issues involved with the planning, development and implementation of Lean Enterprises, including stakeholder value identification and analysis.

Lastly, the reviewed material shown in Figure 2 was utilized in answering the research questions posed in Chapter 1 that focused on how the DoD T&E community can value the use of a decision support system (DSS) for future unmanned autonomous systems of systems test and evaluation.

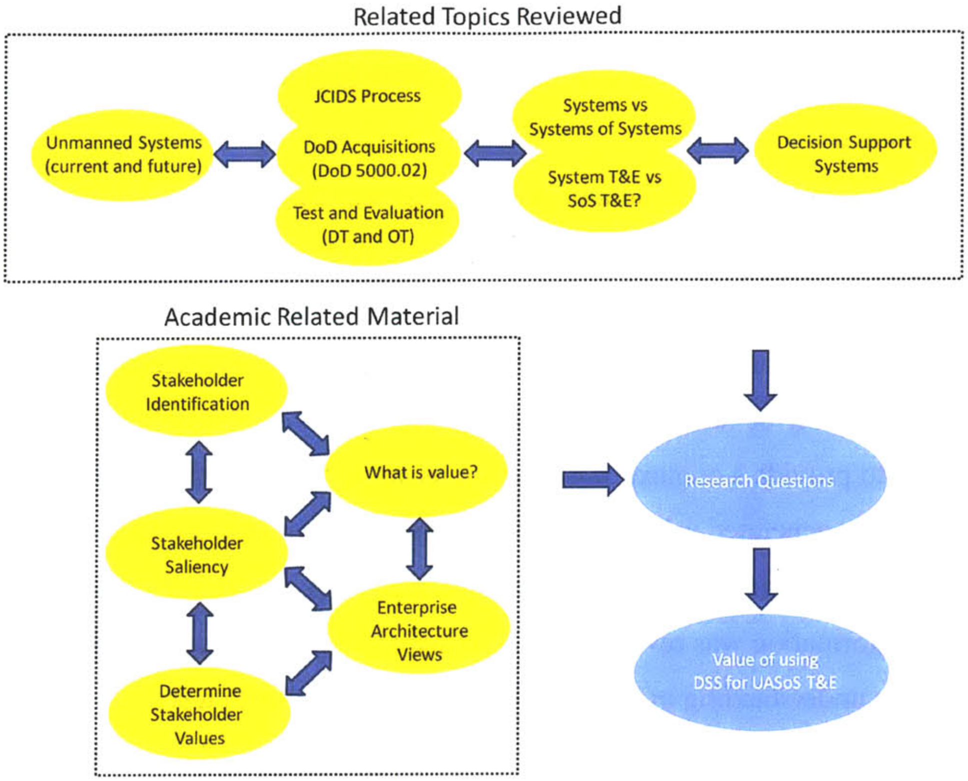


Figure 2 – Literature Review Topics

2.1 – Unmanned Systems and Future Operations

In order to gain perspective, this section will provide a contextual view of how unmanned systems are currently being utilized in order to show the DoD's commitment to their continued development as well as set the stage for the future uses of unmanned systems.

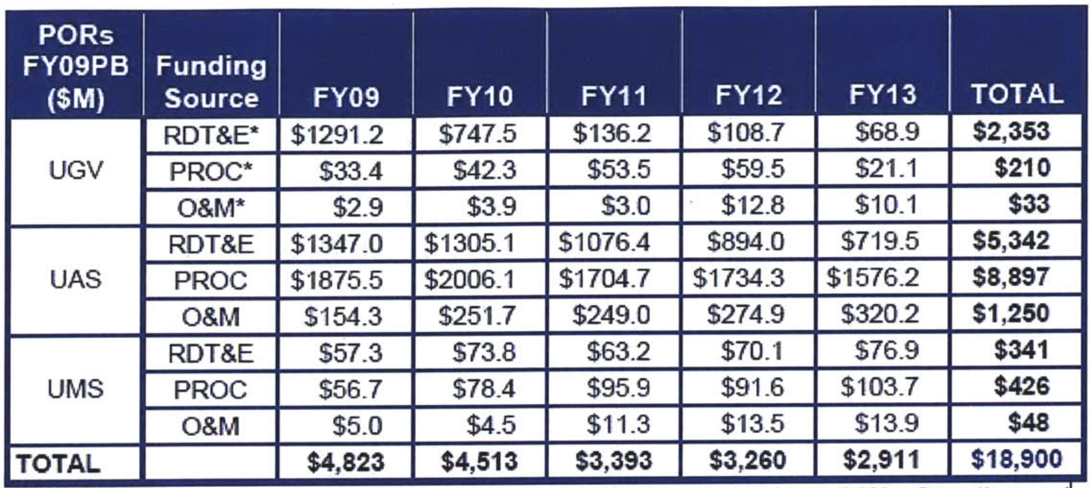
2.1.1 – Current Unmanned Systems

Unmanned systems are being operated by DoD personnel in support of Global Operations such as Operations Iraqi Freedom and New Dawn in Iraq and Operation Enduring Freedom in Afghanistan. Unmanned systems exist for operations in all operational continuums: air, land, sea (surface and below-surface), and space. Table 1 shows the FY 2009-2013 President's Budget for Unmanned Systems, which shows commitment by the DoD in order to develop unmanned system capabilities now and continue their development into the future. One should not be alarmed by the fact that the dollar amounts for each fiscal year decreases. This simply reflects the budget planning process over a five year period and is updated on an annual basis during the development of the defense budget. The DoD FY2009-2034 Unmanned Systems Integrated

Roadmap also identifies eight goals for unmanned systems in order to support the Department's larger goals of "fielding transformational capabilities, establishing joint standards, and controlling costs", which are listed in Table 2 (OUSD(AT&L) 2009a). Note that goal 7 focuses on the ability of being able to test the new unmanned systems in order to ensure they are effective, suitable and survivable. This is important because future unmanned systems will present more complicated scenarios that will have to be verified and validated in order to ensure the appropriate capability is being delivered to the user.

Current unmanned systems that operate in the sky are also known as unmanned aerospace vehicles (UAV) are primarily man-in-the-loop systems and fall into one of five classes. There are numerous models for each UAV operational class as identified in Figure 3. These unmanned systems are not fully autonomous because they all operate with a human-in-the-loop, which calls for a single operator or crew to operate and control the various functions of the UAV such as piloting the vehicle or sensor operator. On one end of the operational spectrum, the Raven, which is classified as a T1 type of UAV, is launched by hand by an US Army infantry soldier in order to conduct intelligence, surveillance and reconnaissance of an area within a 10 mile radius at an altitude of approximately 1,000 feet above ground level (ft AGL) and is operated remotely using a controller similar to that used for a model airplane. On the other end of the spectrum, the Global Hawk, which is classified as an S type of UAV, takes off using a launching apparatus and is controlled by a crew that consists of a pilot and a sensor operator that reside in a remotely located ground station. Also, the Global Hawk is capable of being airborne for upwards of approximately 24 hours at altitudes of 40,000 ft AGL at a maximum radius of about 8,500 miles where it provides persistent intelligence, surveillance and reconnaissance (ISR) coverage over a specific geographic area of responsibility.

Table 1 – FY2009-2013 President's Budget for Unmanned Systems (OUSD(AT&L) 2009a)



PORs FY09PB ($M)	Funding Source	FY09	FY10	FY11	FY12	FY13	TOTAL
UGV	RDT&E*	$1291.2	$747.5	$136.2	$108.7	$68.9	**$2,353**
	PROC*	$33.4	$42.3	$53.5	$59.5	$21.1	**$210**
	O&M*	$2.9	$3.9	$3.0	$12.8	$10.1	**$33**
UAS	RDT&E	$1347.0	$1305.1	$1076.4	$894.0	$719.5	**$5,342**
	PROC	$1875.5	$2006.1	$1704.7	$1734.3	$1576.2	**$8,897**
	O&M	$154.3	$251.7	$249.0	$274.9	$320.2	**$1,250**
UMS	RDT&E	$57.3	$73.8	$63.2	$70.1	$76.9	**$341**
	PROC	$56.7	$78.4	$95.9	$91.6	$103.7	**$426**
	O&M	$5.0	$4.5	$11.3	$13.5	$13.9	**$48**
TOTAL		**$4,823**	**$4,513**	**$3,393**	**$3,260**	**$2,911**	**$18,900**

* RDT&E = Research, Development, Test, and Evaluation; PROC = Procurement; O&M = Operations and Maintenance

Table 2 – DoD Unmanned Systems Development Goals (OUSD(AT&L) 2009a)

Goal	***Description***
1	Improve the effectiveness of COCOM and partner nations through improved integration and Joint Services collaboration of unmanned systems.
2	Support research and development activities to increase the level of automation in unmanned systems leading to appropriate levels of autonomy, as determined by the Warfighter for each specific platform.
3	Expedite the transition of unmanned systems technologies from research and development activities into the hands of the Warfighter.
4	Achieve greater interoperability among system controls, communications, data products, data links, and payloads/mission equipment packages on unmanned systems, including TPED (Tasking, Processing, Exploitation, and Dissemination).
5	Foster the development and practice of policies, standards, and procedures that enable safe and effective operations between manned and unmanned systems.
6	Implement standardized and protected positive control measures for unmanned systems and their associated armament.
7	Ensure test capabilities support the fielding of unmanned systems that are effective, suitable, and survivable.
8	Enhance the current logistical support process for unmanned systems.

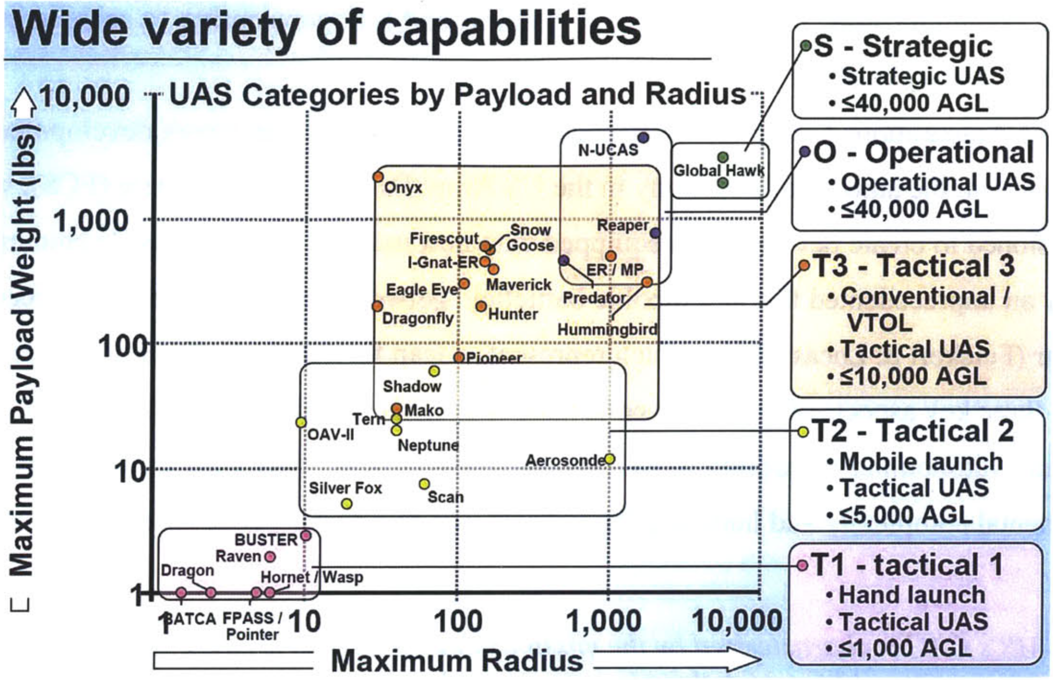


Figure 3 – Unmanned Aerospace Vehicle Spectrums of Designs (Dunaway 2008)

2.1.2 – Future of Unmanned Systems

The Defense Science Board (DSB) was tasked by the Honorable Ashton B Carter to convene a task force to investigate the future role of autonomy in Department of Defense Systems (OUSD(AT&L) 2010). Secretary Carter opens the memorandum to the DSB with the following statement that signifies how future DoD systems will have more autonomy. "Dramatic progress in supporting technologies suggests that unprecedented, perhaps unimagined, degrees of autonomy can be introduced into current and future military systems." This investigation will look at many areas that will surely be impacted by a transition to autonomous systems. One of these focus areas specifies the DSB to "identify special needs in testing and in modeling and simulation to assist in evaluation of specific autonomous enablers and associated concepts of operations." This is important because it signifies the importance that test and evaluation will have on the future of autonomous system capabilities.

Along with classifying system capabilities, future unmanned systems (UMS) will include various levels of autonomy. In this context, autonomy is considered by the National Institute of Standard and Technology (NIST) to be "a UMS's own ability of integrated sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned" (Huang et al. 2007).

The Autonomous Levels for Unmanned Systems (ALFUS) framework development was started based on the amount of autonomy in the US Army Future Combat System (FCS), which was envisioned to create new brigades equipped with new manned and unmanned vehicles linked by an unprecedented fast and flexible battlefield network and aided by various pieces of other gear (Feickert & Lucas 2009), which represents a leap forward in technology. Huang et al. points to three key aspects of UMS that contribute to autonomy and the determination of the Contextual Autonomous Capability (CAC) measurement system , which are mission complexity, environmental complexity and human independence (see Figure 4). As described by Huang et al.:

> *"A UMS's CAC is characterized by the missions that the system is capable of performing, the environments within which the missions are performed, and human independence that can be allowed in the performance of the missions.*
>
> *Each of the aspects, or axes, namely, mission complexity (MC), environmental complexity (EC), and human independence (HI) is further attributed with a set of metrics to facilitate the specification, analysis, evaluation, and measurement of the CAC of particular UMSs.*
>
> *This CAC model facilitates the characterization of UMSs from the perspectives of requirements, capability, and levels of difficulty, complexity, or sophistication. The model also provides ways to characterize UMS's autonomous operating modes. The three axes can also be applied independently to assess the levels of MC, EC, and HI for a UMS."*(2007)

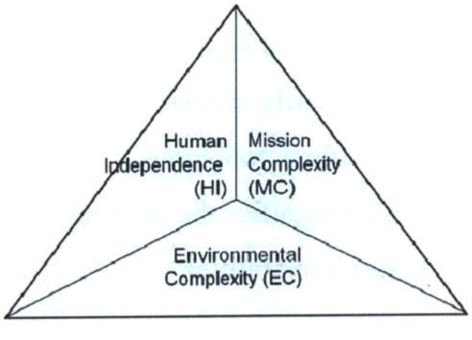


Figure 4 – The Three Aspects of ALFUS (Huang et al. 2007)

It is important to understand what makes of the three aspects of the ALFUS model. Huang et al. provides relative information to the address the three aspects. First, what makes a mission complex? Huang et al. provides the following for the determination of mission complexity (MC):

- *"Mission time constraint*
- *Precision constraints and repeatability, in navigation, manipulation, detection, perception, etc.*
- *Level of collaboration required*
- *Concurrence and synchronization of events and behaviors*
- *Resource management, for including power, bandwidth, and ammunition*
- *Authority hierarchy, for data access, plan execution, etc.*
- *Rules of engagement*
- *Adversaries*
- *Risks, and survivability; for example, signature reduction of self might add to the complexity of the mission*
    - *Knowledge requirements*
    - *Knowledge dependence—types and amounts of information required correlate to mission complexity a priori knowledge might make planning easier*
    - *Knowledge availability, uncertainty, or learning requirement might make the mission more complex*
    - *Difficulty in prediction could affect mission complexity*
    - *Sensory and the processing requirements*
- *HI requirements could affect mission planning and execution, thus affecting mission complexity"* (2007)

Second, what makes an environment more complex? Huang et al. provides the information listed below in order classify what defines environmental complexity (EC):

- *"Energy signals, including*
    - *Acoustic, affecting sensing*
    - *Electromagnetic interference (EMI, also called radio frequency interference or RFI), affecting communication, control, and sensors*
- *Absolute and fiducial (reference points) positioning aides, placement of them, global positioning systems (GPS), markers, etc., can facilitate navigation and reduce the complexity*
- *Dynamic nature*
    - *Stigmergy—environmental effects that were caused by own actions*
    - *Changes in the surroundings that were not caused by own actions*
- *Object size, type, density, and intent; including natural or man made*
- *Fauna and flora, animal and plant lives in regions of interest, respectively*
- *Hazards, including Chemical, Biological, Radiological/Nuclear, and Explosive (CBRNE), fire, etc.*
- *Meteorological data, affecting visibility and traversability*
- *Light*

- *Terrain*
- *Hydrology*
- *Sea state*
- *Positive (hill, bushes) or negative (cave, ditch) features*
- *Engineered structures*
- *Inside, outside*
- *Buildings, bridges, tunnels, trenches, wall, fence, power poles/lines"* (2007)

Third, what makes a UMS human independent? Huang et al. provides the following:

"The more a UMS is able to sense, perceive, analyze, communicate, plan, make decisions, and act, the more independent it is. However, it remains an open issue on how to measure the abilities. For example:

- *When more of the concerned environmental phenomena can be sensed by the UMS*
- *When a wider area of concern can be sensed by the UMS*
- *When the UMS is able to understand and analyze more of the perceived situations*
- *When a larger portion of the mission plan is generated by the UMS*
- *When the UMS is able to generate high-level, complex plans as opposed to low-level, straightforward plans*
- *When the UMS is able to communicate to the right parties with the right information"* (2007)

These three aspects of the ALFUS model help determine the level of autonomy that an UMS is capable of attaining. Haung et al. worked to develop a scale for measuring high, medium and low levels of autonomy using the CAC scale (see Figure 4). Each rating on this scale is based on the combination of HI, MC and EC of the UMS. Current unmanned aerospace vehicles (UAVs) that are utilized today by the DoD operate within a CAC of 2-5 and future UAVs as well as other UMS will potentially operate at higher CAC ratings (see Figure 5).

The information covering unmanned systems shows how the DoD is making investments into its future by supporting the development and commitment to UMS in all operational domains. It is important to point out that many DoD systems that operate today operate under a systems of systems construct, which presents additional challenges that need to be overcome and will be defined later in this chapter. Also, as pointed out by Secretary Carter, future DoD systems will have autonomous aspects where the systems will be unmanned and able to be self aware and recognize the physical environment in which they operate as defined by Huang at al. (2007). Thus, they will be operating in unmanned autonomous systems of systems (UASoS).

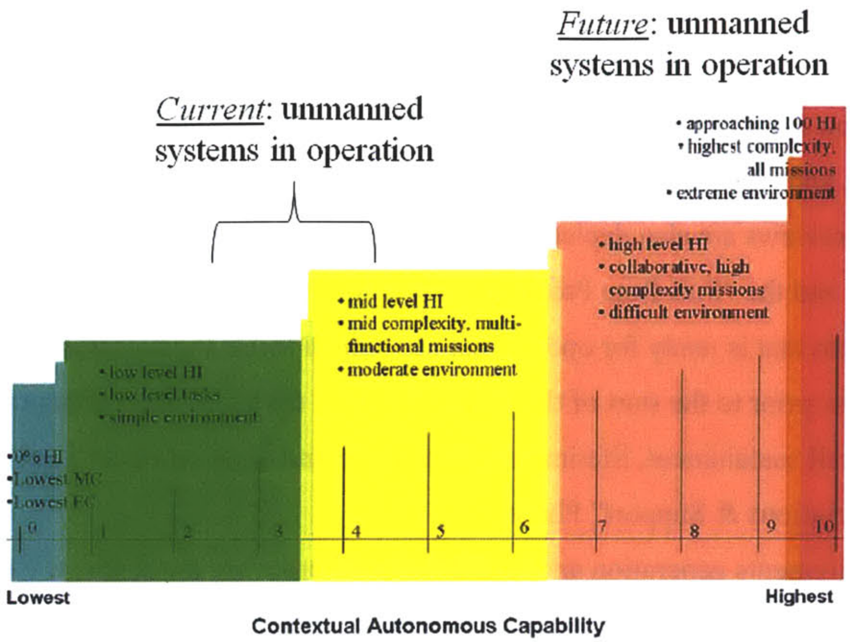


Figure 5 – CAC Rating Scale for UMS (Huang et al. 2007)

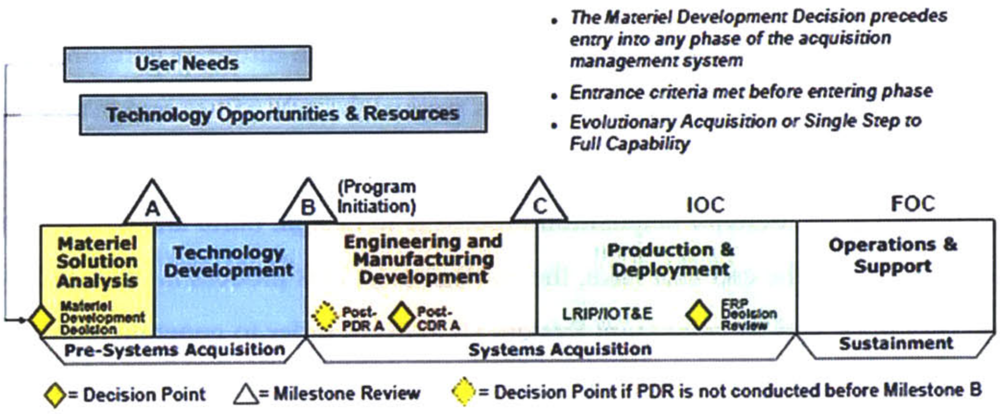
2.2 – Defense Acquisition

The previous section focused on the status of current unmanned systems and how the DoD is looking to develop autonomous unmanned systems in the future. Therefore, it is important to review the DoD acquisition process as well as the role of test and evaluation for a system and a SoS because these present additional challenge areas for UASoS.

The purpose of the defense acquisition process is to design, build and test systems that meet the requirements of the end user (aka, the warfighter). This process is preceded by the Joint Capabilities Integration and Development System (JCIDS) in order to generate requirements. JCIDS, which is governed by the Chairman of the Joint Chiefs of Staff (CJCS) Instruction 3170.01 and Manual 3170.01, ensures the military requirements are valid, clear and do not replicate existing requirements (DoD 2009). Prior to the start of an acquisition program, there needs to be an identified user need as well as an approved and authorized budget by the Department of Defense (DoD) and the President of the United States.

The defense acquisition process is governed by DoD Instruction 5000.02, *Operation of the Defense Acquisition System*, and serves the purpose of establishing a management framework for translating capability needs into acquisition programs (OUSD(AT&L) 2008a). This management framework contains a series of life cycle phases and critical milestones each program must go through. Figure 6 depicts the complete acquisition process beginning with "Materiel Solution Analysis" and concludes with "Operations & Support" of the new system. Milestones A, B, and C are points in the process where major approval is granted in order to continue. Major reviews are also depicted such as the "Preliminary Design Review", "Critical Design Review" and the "Full-Rate Production Decision Review". The result of the acquisition process is a system that is ready for operational use, which meets the requirements developed by the JCIDS process prior to the start of the program. Also, the acquisition community often plays a role in the overall sustainment, lifetime modernization and disposal of the system as it ages through the "Operations & Support" Phase.

The requirements generation and acquisition processes are areas where UASoS face further challenges because requirements development might not capture all of the needs of the user or may result in inadequate requirements. Also, additional challenges are presented by the acquisition process because it focuses only on acquisition of a single system vice a system of systems.



MDD – Materiel Development Decision
PDR – Preliminary Design Review
CDR – Critical Design Review
LRIP – Low Rate Initial Production
IOT&E – Initial Operational Test & Evaluation
FRP – Full Rate Production
IOC – Initial Operational Capability
FOC – Full Operational Capability

Figure 6 – Defense Acquisition Process (DoD 2008)

2.3 – A System and Systems of Systems

In addition to challenges with autonomy levels, requirements generation, and acquisitions, it is important to distinguish between a system and systems of systems. In order to provide insight into differences between a system and systems of systems, some key definitions are provided. This is done in order to demonstrate some additional levels of complexity that will be present in the acquisition and development of UASoS.

2.3.1 – Systems

DoD SE Guide for SoS: A functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements; that group of elements forming a unified whole (ODUSD(A&T) 2008).

International Council on Systems Engineering (INCOSE): A combination of interacting elements organized to achieve one or more stated purposes; an integrated set of elements, subsystems, or assemblies that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements. (INCOSE 2010).

One of the challenges for modern day DoD systems is the level of complexity that exist within the design and the difficulty in overcoming complex challenges that lead to cost overruns, longer than planned delivery schedules and underperformance in the promised technologies. For example, the US House of Representatives Armed Services Committee (HASC) conducted a panel review for acquisition reform and found that "only 16% of IT (information technology) projects are completed on time" (USHR 2010). Also, the HASC found that "31% are cancelled before completion"; "the remaining 53% are late and over budget with a typical cost growth of by more than 89%"; and "of the IT projects that are completed, the final product contains only 61% of the originally specified features" (USHR 2010). Another example of growing complexity within DoD systems is reflected in Table 3, which shows the upward trend of software utilization in DoD aircraft representing a growth of 900% from the F-4 in 1960 to the F-22 in 2000 (Coyle 2010).

Table 3 – Software in DoD Systems (Coyle 2010)

Weapon System	Year	% Functions Performed in Software
F-4	1960	8
A-7	1964	10
F-111	1970	20
F-15	1975	35
F-16	1982	45
B-2	1990	65
F-22	2000	80

2.3.2 – Systems-of-Systems – Definitions and Characteristics

Sauser and Boardman summarized and synthesized current definitions (see Table 4) relating to system and systems of systems (2006):

- System – an assemblage of inter-related elements comprising a unified whole
- Complex System – highly structured; contains variations; evolves over time; independently interacting components
- Complex Adaptive Systems (this is a special case of complex systems) – simple/autonomous and richly interconnected elements; dynamic with many agents; order is emergent; history is irreversible; unpredictable
- Systems of Systems – Sauser identified over 40 different definitions in the literature; Table 4 provides a summary of the differences found between systems and systems of systems (a more detailed version of table data is included in Appendix E)

Based on the current taxonomy, there are four types of recognized SoS that are found in the DoD (Maier 1998; Dahmann & Baldwin 2008). These are:

- *Virtual*: Virtual SoS lack a central management authority and a centrally agreed upon purpose for the system-of-systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it.
- *Collaborative*: In collaborative SoS the component systems interact more or less voluntarily to fulfill agreed upon central purposes. The Internet is a collaborative system.

The Internet Engineering Task Force works out standards but has no power to enforce them. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.

- *Acknowledged*: Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
- *Directed*: Directed SoS are those in which the integrated system-of-systems is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

Table 4 – Systems vs Systems of Systems (Sauser & Boardman 2006)

Element	***System***	***Systems of Systems***
Autonomy	Ceded by path	Exercised by constituent systems
Belonging	Parts do not choose	Constituent systems choose to belong
Connectivity	Hidden in elements, minimum between subsystems	Dynamically supplied, myriad of possible, net-centric architecture
Diversity	Reduced/minimized	Increased, achieved by released autonomy
Emergence	Foreseen, both good and bad, and designed in or tested out early	Enhanced by deliberately not being foreseen, bad behaviors detected and removed early

The DoD Systems Engineering Guide for Systems of Systems states the following in regards to the Acknowledged Systems of Systems (ODUSD(A&T) 2008):

> "In the DoD today, we see a growing number of acknowledged SoS. Like directed SoS, acknowledged SoS have recognized authorities and resources at the SoS level. However, because an acknowledged SoS comprises systems that maintain independent objectives, management, and resources, along with independent development processes, these SoS are largely collaborative in practice. For systems in these SoS, in particular, their normal operational mode is **not** subordinated to the central managed purpose—a distinct feature of a directed SoS. Because defense acquisition and funding are still largely platform focused, many SoS do not have authority over the systems, and they typically try to address SoS objectives by leveraging the developments of the systems, which are normally more long-standing and better supported than the SoS. Consequently, acknowledged SoS, like

> directed SoS, have objectives, management, and funding without authority over the constituent systems. Like collaborative SoS, changes in systems to meet SoS needs are based on agreement and collaboration, not top-down authority from the SoS manager.
>
> As the DoD increases focus on capabilities without changing its system-oriented organization, the number of acknowledged SoS is increasing. User capabilities call for sets of systems working together toward the capability objectives. In many cases, the DoD is choosing to leverage existing systems to support these capabilities. The current needs for these systems persist, however, leading to instances of acknowledged SoS where there are legitimate objectives, management, and funding at both the capability and system levels." (ODUSD(A&T) 2008)

The DoD Systems Engineering Guide for Systems of Systems defines an SoS as a "set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" (ODUSD(A&T) 2008). Also, the DoD SoS SE Guide compares systems to SoS in a similar fashion as Sauser and is shown in Table 5.

Understanding the differences of the operating environments between a system and systems of systems is critical in order to understand the many challenges that will be faced as these capabilities are developed. As can be seen from Table 5, the test and evaluation of an individual system is "generally possible". But, the T&E of an SoS is more difficult due to the fact there are multiple systems at potential various life cycle stages. The next section will provide more detail into test and evaluation, which has the primary roles of verification and validation of the system undergoing T&E and will prove to be a significant hurdle to overcome with UASoS.

Table 5 – Systems vs Systems of Systems (ODUSD(A&T) 2008)

Aspect of Environment	*System*	*Acknowledged System of Systems*
Management & Oversight		
Stakeholder Involvement	Clearer set of stakeholders	Stakeholders at both system level and SoS levels (including the system owners), with competing interests and priorities; in some cases, the system stakeholder has no vested interest in the SoS; all stakeholders may not be recognized
Governance	Aligned Program Management and funding	Added levels of complexity due to management and funding for both the SoS and individual systems; SoS does not have authority over all the systems
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet a set of operational objectives using systems whose objectives may or may not align with the SoS objectives
Implementation		
Acquisition	Aligned to ACAT Milestones, documented requirements, Systems Engineering with a Systems Engineering Plan (SEP)	Added complexity due to multiple system lifecycles across acquisition programs, involving legacy systems, systems under development, new developments, and technology insertion; Typically have stated capability objectives upfront which may need to be translated into formal requirements
Test & Evaluation	Test and evaluation of the system is generally possible	Testing is more challenging due to the difficulty of synchronizing across multiple systems' life cycles; given the complexity of all the moving parts and potential for unintended consequences
Engineering & Design Considerations		
Boundaries and Interfaces	Focuses on boundaries and interfaces for the single system	Focus on identifying the systems that contribute to the SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems
Performance & Behavior	Performance of the system to meet specified objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems

2.4 – Test and Evaluation in the DoD Acquisition Process

2.4.1 – Test and Evaluation Description

Test and Evaluation is primarily a part of the systems engineering process that is utilized during the development of the system. It is the mechanism used in the verification and validation against the user requirements of the system that is being fielded. In the simplest of terms Test and Evaluation can be defined in its two parts: 1) test and 2) evaluation. Test or testing is a systematic means of collecting data which can be analyzed and used to formulate statements regarding the performance of a component, system or concept that is within certain limits of error. Evaluation is the process by which one examines the test data and statements, as well as any other influencing factors, to arrive at a judgment of the significance or worth of the component, system or concept (Giadrosich 1995).

2.4.2 – Reducing Risks through Test and Evaluation

The primary purpose of T&E during the acquisition process is to allow the reduction of risk, either the risk that the system or equipment will not meet performance specifications or the risk that the system or equipment cannot be effectively employed in its intended combat environment (Giadrosich 1995). T&E is the principal means of demonstrating that program objectives can be met and is typically broken down into Developmental Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E).

2.4.3 – Definition of Developmental Test and Evaluation

Developmental testing is conducted throughout the acquisition and sustainment processes to assist in engineering design and development and verify that critical technical parameters (CTP) have been achieved. Developmental test and evaluation (DT&E) supports the development and demonstration of new materiel or operational capabilities as early as possible in the acquisition life cycle. After full-rate production (FRP) or fielding, DT&E supports the sustainment of systems to keep them current or extend their useful life, performance envelopes, and/or capabilities. As many test activities as practical are conducted in operationally relevant environments without compromising engineering integrity, safety, or security. Developmental testing must lead to and support a certification that the system is ready for dedicated operational testing (USAF 2009a).

2.4.4 – Definition of Operational Test and Evaluation

According to Title 10, United States Code, "Operational test and evaluation means – the field test, under realistic combat conditions, of any item of (or key component of) weapons, equipment, or munitions for use in combat by typical military users; and the evaluation of the results of such test" (Title 10 2010)

Further, operational testing determines if capabilities-based requirements have been satisfied and assesses system impacts to both peacetime and combat operations. It identifies and helps resolve deficiencies as early as possible, identifies enhancements, and evaluates changes in system configurations that alter system performance. Operational testing includes a determination of the operational impacts of fielding and/or employing a system across the full spectrum of military operations and may be conducted throughout the system life cycle. Operational testing may also look at doctrine, operational concepts, system performance, TTPs, logistics support elements, intelligence support elements, system interoperability and security, materiel issues, safety, training, organization, human systems integration (HSI), and personnel (USAF 2009a).

2.4.5 – Ideals of Test and Evaluation

T&E results are relied upon heavily by acquisition decision makers and system operators. Congressional officials and other high level government executives are highly dependent upon T&E to provide timely, unbiased quantitative input to decisions. Combat users must have essential system information that can be derived in no other manner. T&E results represent the most credible source of information available. Consequently, it is imperative that those who are charged with the conduct of T&E maintain the highest ideals and standards: integrity, objectivity, operational realism, and scientific validity (Giadrosich 1995).

2.5 – System T&E versus Systems of Systems T&E

As stated earlier, T&E is part of the systems engineering process with the roles of verification and validation. At the system level, verification confirms that the system element meets the design-to or build-to specifications and answers the question "Did you build it right?" and validation answers the question of "Did you build the right thing?" (ODUSD(A&T) 2008).

Verification and validation will also play significant roles in the SoS. Verification will primarily take place in order to orchestrate upgrades to the SoS where activities might "include demonstration, inspection, similarity considerations, and tests at the system level" (ODUSD(A&T) 2008). SoS validation will be applied in order to assess SoS performance capability objectives as well as orchestrate upgrades in order to assess "whether the changes made in the SoS have the desired end-to-end effects" (DoS SoS 2008).

Test and Evaluation for a system is complex, but it is even more complex whenever it is conducted for a SoS. Dahman et al. identified seven SoS T&E challenges shown in Table 6 (2010).

In addition to the SoS T&E challenges specified by Dahman et al, the Defense Science Board stated that "testing all SoS requirements of all the systems is impossible"; and recommended the formulation of "alternative strategies to adapt current requirements, acquisition and funding processes to enable timely, efficient and effective T&E of SoS capabilities" (OUSD(AT&L) 2008b).

Table 6 – SoS Test and Evaluation Challenges (Dahman et al. 2010)

Number	*SoS T&E Challenge Information*
1	SoS validation criteria are more difficult to establish
2	SoS conditions cannot be explicitly imposed on individual system T&E
3	No clear analogs between SoS level objectives and those of the individual systems
4	Acquisition decisions are based on individual system and SoS level testing
5	Asynchronous individual system schedules make it difficult for SoS testing events
6	SoS require more test points for detecting emergent behaviors
7	SoS increases subjectivity in assessing behavior as well as presenting challenges to the system alignment

Thus far, many challenges have been identified for both the future of unmanned autonomous systems and SoS T&E. There needs to be a solution that exists in order to overcome these challenges. One possible solution is a Decision Support System (DSS), which is discussed in the next section. In simple terms, a DSS allows pertinent information to be collected and presented in a way for decisions to be made in complex environments.

2.6 – Decision Support Systems

Decision support systems (DSS) refer to information systems that support organizational decision making (Keen 1978). Traditionally, DSS were tailored to the needs of individual users, but evolved to support multiple decision makers through Group Decision Support Systems (GDSS) (DeSanctis & Gallupe 1987) and Organizational Decision Support Systems (ODSS) (Carter et al. 1992). The basic architecture of a DSS consists of three components: a database, a model and a user interface. As such, research in database design, software engineering and user interface design have significantly contributed to DSS development. Furthermore, Intelligent Decision Support Systems (IDSS) refer to DSS that leverage artificial intelligence technologies for decision making. With emphasis on distributed decision making, networking technologies have become increasingly important for DSS implementation. DSS have found numerous applications that include financial planning systems, clinical DSS for medical diagnostics, and executive decision making systems for performance analysis, resource allocation, and planning. While traditional DSS are often tailored to support specific types of organizational decision making, recent work has proposed an Integrated Decision Support Environment (IDSE) to 'integrate capabilities from a set of systems to configure a computer environment for varied decisions under varied situations' (Lui et al. 2008). An important challenge that needs to be addressed in the T&E domain is the development of DSS at the organizational level that can support joint testing efforts and varying stakeholder needs.

A proposed way of addressing this T&E challenge is via a DSS called *PATFrame*, as mentioned in Chapter 1. *PATFrame* is intended to be a prescriptive and adaptive framework for unmanned autonomous systems of systems (UASoS) testing in order to address critical needs and challenges facing the unmanned autonomous systems test (UAST) community (Valerdi et al. 2008). The objectives of *PATFrame* include: (1) develop an understanding of the theoretically best SoS test strategies through a normative framework, (2) determine the best in class test strategies available across industry and government through a descriptive framework, (3) develop a prescriptive framework for improving decision making according to normative and descriptive standards, and (4) provide a decision support tool that will enable improved decision making for the UAS T&E community. The effort includes the development of an adaptive architectural framework for SoS testing and it is a framework that provides a key and unique contribution: the capability to predict when a test system needs to adapt. The framework is an innovative integration of control-theory-based adaptation and multi-criteria decision making. Additional technical information about to *PATFrame* is included in Appendix A.

The aforementioned material covered unmanned systems; DoD requirements generations and acquisitions; differences between systems and systems of systems as well as test and evaluation. Each area covered identified challenges to the development of UASoS and the T&E enterprise. A possible solution is on the table in the form of *PATFrame*. In order to effectively utilize *PATFrame* and deliver its intended value, the T&E enterprise will need to transform. The remaining material in this chapter defines value creation and delivery as well as enterprise transformation along with stakeholder identification. These are important topics because they represent key aspects that need to be understood in order for the T&E enterprise to transform and conduct future verification and validation of UASoS.

2.7 – Value and Enterprise Transformation

The function of an enterprise is to be able to deliver value to its stakeholders. Various definitions of value are depicted in Table 7. Ultimately, these definitions have the commonality of the following traits: cost, schedule and performance. This is important because the concept of systems of systems is a balance of these three categories.

Value cannot be delivered without understanding the expectations of the stakeholders. In order to deliver the value to the stakeholders of an enterprise, the steps outlined by Murman et al. shown in Figure 7 should be followed. The first step is value identification, which starts with identifying the stakeholders and their value needs or requirements (Murman et al. 2002). The most efficient process utilized to identify the needs or requirements of the stakeholders are interviews. The value proposition is the phase where the needs of the key stakeholders come together . The first two steps of the process are important to understand in order to achieve value delivery to the stakeholders because some businesses only focus on value delivery and fail (Murman et al. 2002). Value delivery is where the stakeholder receives the actual value from the product, service or process that is being utilized (Murman et al. 2002). In achieving value delivery one understands the relative value importance of the enterprise to the stakeholders as well as the current value delivery. If the value delivered does not meet stakeholder expectations, then iterations within the value creation process take place in order to close any identified gaps.

In delivering value, transformation needs to take place within an enterprise as the mission focus or purpose of the enterprise takes shape. This is the case for the test and evaluation enterprise of the DoD as well as industry. With the advent of unmanned autonomous systems of systems, the DoD's manned system focused T&E enterprise will need to morph into an enterprise construct that will be able to face the future challenges. Nightingale and Srinivasan have identified several key principles (Table 8) that provide insight for Enterprise Transformation that will be utilized in this thesis (2011) in order to effectively change the enterprise and deliver value to the stakeholders.

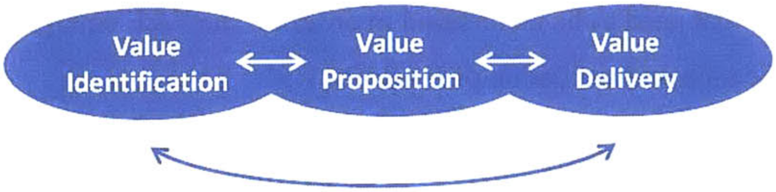


Figure 7 – Value Creation Iterates and Adapts (Murman et al. 2002)

Table 7 – Value Definitions [adopted from (Burgess 2010)]

Value Definitions
Value is the appropriate performance and cost. (Miles 1961)
Lowest cost to reliably provide required functions or service at desired time and place and with the essential quality. (Mudge 1971)
Value is function divided by cost. (Kaufman 1985)
Value is the potential energy function representing the desire between people and products. (Shillito & DeMarle 1992)
Value is a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer. (Womack & Jones 1996)
The additional functionality of a product normalized by the cost of the additional functionality, or simply function divided by cost. (Cooper & Slagmulder 1997)
Value is anything that directly contributes to the "form, fit, or function" of the build-to package or the buy-to package Form: Information must be concrete format, explicitly stored Fit: Information must be (seamlessly) useful to downstream processes Function: Information must satisfy end user and downstream process needs with an acceptable probability of working (risk) (LAI 1998)
[Value is] balancing performance, cost, and schedule appropriately through planning and control. (Browning 1998)
Value is a measurement of the worth of a specific product or service by a customer and is a function of: (1) Product's usefulness in satisfying customer needs; (2) Relative importance of the need being satisfied; (3) Availability of the product relative to when it is needed; (4) Cost of ownership to the customer. (Slack 1999)
[Value is] a system introduced at the right time and right price which delivers best value in mission effectiveness, performance, affordability and sustainability and retains these advantages throughout its life. (Stanke 2001)
Definition of value centers on exchanges that provide utility or worth and the result from some organizational action based on how various stakeholders find particular worth in exchange for their respective contributions to the enterprise. (Murman et al. 2002)
Value is an outcome of balancing system level goals, function and cost. (Crawley 2009)

Table 8 – Enterprise Transformation Principles (Nightingale & Srinivasan 2011)

Enterprise Transformation Principles
Adopt a holistic approach to enterprise transformation
Secure leadership commitment to drive and institutionalize enterprise behaviors
Indentify relevant stakeholders and determine their value propositions
Focus on enterprise effectiveness before efficiency
Address internal and external enterprise interdependencies
Ensure stability and flow within and across the enterprise
Emphasize organizational learning

Further explanations of the principles listed in Table 8 are provided here. In order to adopt a holistic approach to enterprise transformation, Nightingale and Srinivasan state the following:

> *"In the context of enterprise transformation, 'holistic' emphasizes the need to understand the impact of transformation on the enterprise as a whole. Strategically, a holistic enterprise view is the articulation of who the relevant stakeholders of the enterprise are and what they value. It is a deep understanding of the core capabilities and competencies of the enterprise and an assessment of whether the enterprise as currently constructed can deliver the value required from it. From an operational perspective, it is having the required resources to deliver on the enterprise value proposition: having the right leaders, capturing the right knowledge, and having the right people and processes to create the required value"* (2011).

This principle is relevant to T&E of UASoS because changing single aspects of the enterprise vice a holistic change is only a partial solution to overcoming the challenges.

Nightingale and Srinivasan call for a secure leadership commitment to drive and institutionalize enterprise behaviors:

> *"It is absolutely critical that enterprise transformation be driven, first, from the highest levels of the enterprise. A transformation effort must have the full commitment of the senior leadership team. A process must then unfold to "distribute" that leadership commitment throughout the enterprise. The institutionalization of enterprise behaviors that follows – that is, the adoption of a holistic approach to transformation from top to bottom in the enterprise –makes success achievable"* (2011)

This is important to UASoS T&E because of the bureaucratic nature of the enterprise. Transformation must start at the top.

Nightingale and Srinivasan state the identification of relevant stakeholders and the determination of their value proposition is important:

> *"A basic requirement for successful transformation is having an understanding of the enterprise value proposition, and ensuring that the constructed value proposition is a true reflection of the values of its stakeholders. When the enterprise leaders understand stakeholder value, they can then assess how to deliver the value expected by its stakeholders. It is not enough for the enterprise to identify its stakeholders, but the enterprise must also determine why a given stakeholder is important (the stakeholder's salience). This allows the enterprise to make informed decisions about whether the value proposition is correct and whether it is viable over the long term"* (2011)

The identification of the relevant UASoS stakeholders is important because the true impact of change will be based on understanding the stakeholders needs and expectations.

Nightingale and Srinivasan call for a focus on enterprise effectiveness before efficiency:

> *"Doing the right job and doing the job right – these capture the notions of effectiveness and efficiency. An effective enterprise requires a value proposition that meets the current needs of stakeholders and is perceived to be able to meet their future needs.. If you are able to execute at a lower cost (where cost is some function of resource utilization), yours is an efficient enterprise"* (2011)

This principle applies directly to the architecture of UASoS T&E. It is important to understand the interactions of the complexities before trying to take shortcuts that might prove to be costly in the long run.

An enterprise needs to address it internal and external interdependencies:

> *"Every enterprise is a highly integrated system whose performance is determined by the degree of alignment among the major elements. These include the key structures, policies, processes, and stakeholders in the enterprise. One of the most difficult challenges in enterprise transformation is to specify the boundaries of the enterprise, because what is internal to the enterprise at one time may not necessarily remain within the boundaries as the enterprise evolves and transforms. With the boundaries identified, the structures, policies, and processes need to be mapped so interdependencies can be determined. A successful transformation effort must account for both the internal and the external interdependencies"* (2011)

This is applicable because the relationships between the constituent systems will need to be well understood through the development life cycle of an UASoS.

Another principle offered by Nightingale and Srinivasan is to ensure stability and flow within and across the enterprise:

> *"Stability provides the foundation for creating a baseline against which enterprise performance can be assessed. In the presence of stability, flow within the enterprise enables you to see the presence of bottlenecks and identify root causes to problems. Both are central to any transformation effort. ... When the enterprise environment is turbulent, only the 'tip of the iceberg is visible' and attempts to navigate around the iceberg may be disastrous if the underlying problems are not understood. In an environment of stability and flow, more of the iceberg can be seen by lowering the water level through problem solving that focuses on revealing the root causes of the problems."* (2011)

This is applicable to T&E of UASoS because as identified by Dahman et al., asynchronous schedules and changing requirements are a couple of challenges that will need to be continuously monitored and understood.

Lastly, Nightingale and Srinivasan call for an emphasis on organizational learning:

> *"Emphasizing organizational learning is as much about creating the context and culture to support a learning organization as it is about establishing the formal structures and policies that govern the learning process. In the transformation context, organizational learning can happen through exploration, as stakeholders engage in distributed*

> *sensemaking to determine potential areas of improvement, or through exploitation, as well-understood, well-governed transformation tools and techniques are deployed"* (2011)

This last principle is especially important because a UASoS T&E knowledge base will have to be formed and continuously maintained in order to the enable the enterprise to the deliver.

2.8 – Enterprise Architecture

Enterprise Architecture, as prescribed by Nightingale and Rhodes, is a strategic approach which takes a systems perspective, viewing the entire enterprise as a holistic system encompassing multiple views such as organization view, process view, knowledge view, and enabling information technology view in an integrated framework" (2004). A holistic view must be applied when looking at enterprises because they do not lend themselves to a traditional decomposition approach used in the analysis of complex systems (Nightingale & Rhodes 2004). This is driven by the fact that an enterprise is a highly networked system and the architect needs to balance the needs of multiple stakeholders working across boundaries (Nightingale 2010). This stipulates that all views must be examined because they are linked to each other and provide key relationships to how the enterprise performs. As time has passed, Nightingale and Rhodes have refined the views to include: strategy, policy/external factors, organization, process, knowledge, information, product, and services (Rhodes, Ross and Nightingale 2009).

In order to conduct a holistic analysis of an enterprise, Nightingale and Rhodes developed an eight view enterprise architectural framework that includes the following views: strategy, process, organization, knowledge, information, service, product and policy. Definitions of each view are explained in Table 9. Also, all eight views and their relationships with one another are shown in Figure 8. This type of analysis framework applies to this research because it will allow for an understanding of the individual T&E enterprise components relative to UASoS testing. This will culminate into a holistic analysis of the enterprise once all eight views are examined and will identify areas that need to be changed in the future. Each view provides the ability analyze the enterprise through the subject lenses. Once, each view analysis is conducted, then the holistic view of the enterprise can be conducted. This provides a complete sight picture of the enterprise and also identifies potential areas of the enterprise that need to the be changed in order to increase stakeholder value.

It is important to point out that Enterprise Architecture can also apply to systems of systems. This is reinforced by Rouse who proposed thinking of an enterprise as a system or system of systems and defined an enterprise as "a goal-directed organization of resources—human, information, financial, and physical—and activities, usually of significant operational scope, complication, risk, and duration" (2005). This applies to this thesis because the enterprise that is being evaluated is the Test and Evaluation enterprise of the DoD and testing unmanned systems in the SoS environment. The T&E enterprise fits Rouse's definition because it has goals in conducting verification and validation activities of the systems that are being tested, which requires significant amount of resources and activities.

A key strategy for Enterprise Architecture is that it allows the architect to determine the "As-Is" state of the enterprise in order to holistically evaluate the current state of an enterprise. In doing this, the architect is able to envision the areas in the enterprise where improvement can be made in order to deliver value to the stakeholder by determining new possible configurations for the enterprise based on the needs of the stakeholders. One way of instituting change in an enterprise in order to deliver value to the stakeholder is through the –ilities. The –ilities as described by McManus et al. provide a criteria system for evaluation and are defined as "system properties that specify the degree to which systems are able to maintain or even improve function in the presence of change" (2007). Eight –ilities are discussed and include the following: Robustness, Versatility, Changeability, Flexibility, Adaptability, Scalability, Modifiability and Survivability. Definitions are provided below (Rhodes & Ross 2008).

- *Robustness* – ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal interfaces
- *Versatility* – ability of a system to satisfy diverse expectations on the system without the need for changing form
- *Changeability* – ability of a system to alter its form and/or function at an acceptable level of resource expenditure (i.e., time, money & materials)
- *Flexibility* – ability of a system to be changed by a system-external change agent
- *Adaptability* – ability of a system to be changed by a system-internal change agent
- *Scalability* – ability to change the current level of a system specification parameter
- *Modifiability* – ability to change the current set of system specification parameters

Table 9 – Enterprise Architecture Views (Nightingale 2009)

View	*Description*
Strategy	Strategic goals, vision & direction of the enterprise including the business model; enterprise metrics & objectives
Policy/External Environment	External regulatory, political & societal environments in which the enterprise operates
Process	Core leadership, lifecycle & enabling processes by which the enterprise creates value for its stakeholders
Organization	Organizational structure of the enterprise as well as relationships, culture, behaviors & boundaries between individuals, teams & organizations
Knowledge	Implicit & tacit knowledge, capabilities & intellectual property resident in the enterprise
Information	Information needs of the enterprise, including flows of information as well as the systems and technologies needed to ensure information availability
Product	Product(s) developed by the enterprise; key platforms; modular vs. integral architectures, etc.
Services	Services(s) delivered and or supplied by the enterprise, including in support of products

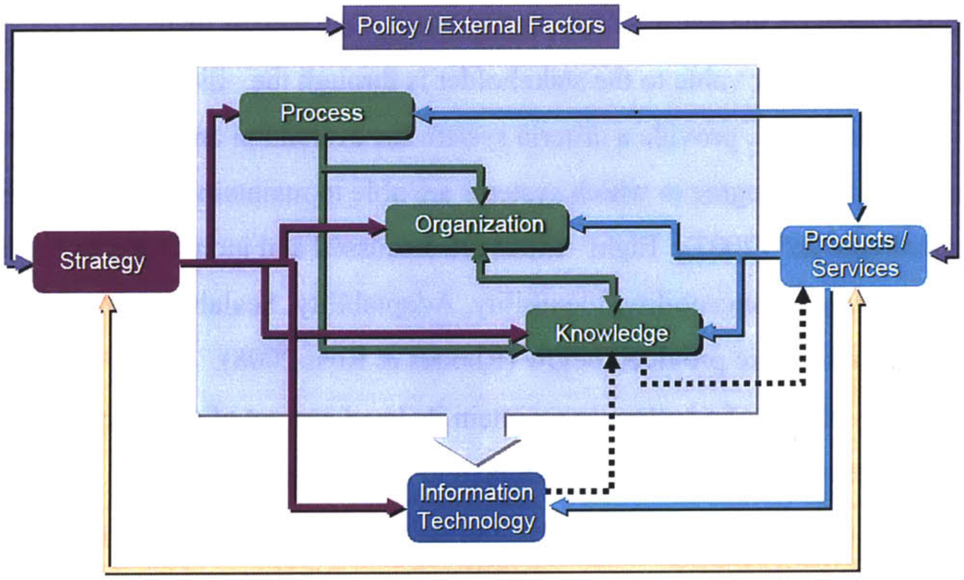


Figure 8 – Eight View Enterprise Architecture Framework (Nightingale 2009)

2.9 – Stakeholders and Saliency

There are two steps in dealing with enterprise stakeholders. The first is to identify the stakeholders that impact the enterprise and the second step deals with the saliency of the stakeholders. In dealing with stakeholder identification, Mitchell, Agle and Wood define a stakeholder as "any group or individual who can affect or is affected by the achievement of the organization's objectives" (1997). There is also the inclusion factor to consider, which basically calls for judgment into who to consider as a stakeholder. The stakeholders of an enterprise could be confined to those who are just essential for the achievement of overall business objectives, or a broader approach can be taken where anyone the enterprise might affect can be considered a stakeholder (Murman, et al. 2002). Each enterprise has its own particular set of stakeholders, but most include those shown in Figure 9. See Table 10 for definitions for each of the stakeholder groups. An important aspect in regards to stakeholders is that depending on the size of the undertaking stakeholder identification and the size and complexity of the enterprise being analyzed, it may be necessary to reduce the number of stakeholders to some manageable number, which up the topic of stakeholder saliency. (Nightingale & Srinivasan 2011).

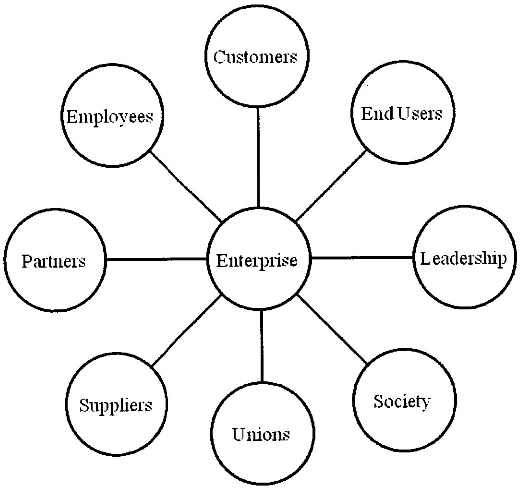


Figure 9 – Generic Enterprise Stakeholders (Nightingale & Srinivasan 2011)

An important stakeholder attribute that Mitchell, Agle and Wood added to stakeholder theory was an identification process that could reliably separate true stakeholders from nonstakeholders, which is also known as stakeholder salience (1997). They accomplished this by developing a theory where each stakeholder possesses one or more of three key attributes that are of interest to the enterprise. Mitchell, Agle and Wood show these three attributes to be *Power*, *Legitimacy* and *Urgency*, where:

- *Power* is "a relationship among social actors in which one social actor, A, can get a another social actor, B, to do something that B would not have done otherwise" and is based on coerciveness and utilitarianism
- *Legitimacy* is "a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs and definitions" and is based on the individual, organization or society
- *Urgency* is "the degree to which stakeholder claims call for immediate attention" and is based on the time sensitivity of an action along with its criticality.

Table 10 – Common Stakeholder Groups (Nightingale & Srinivasan 2011)

Stakeholder Group	**Definition**
Customers	Customers specify requirements and pay money in return for products and services delivered.
End Users	End Users specify requirements based on actual use or consumption of products and services delivered. They may or may not be customers. For instance, an airline is the customer, while the passenger is the end user.
Suppliers	Suppliers deliver products and services based on requirements specified by the enterprise in exchange for money.
Partners	Partners are suppliers with whom the enterprise has a close relationship, often involving risk and reward sharing, long-term interaction, and codependency.
Employees	Employees are all people who work for the enterprise, either directly or on site as contract employees. This includes employees represented by unions.
Unions	Unions are formal organizations of employees who have banded together to achieve common goals, which could include better wages, working conditions, and so on. In organizations that do not have formal unions, this stakeholder group would include employee associations and other informal employee groups.
Leadership	Leadership internal and external to the enterprise provides strategic direction and allocate resources to be used by the enterprise. In some cases, leadership may include other organizational units.
Society	Society includes the local communities where the enterprise exists and in which the enterprise does business (or operates). This often includes government representatives working at various levels (tax authorities, environmental compliance).
Shareholders	Shareholders provide the enterprise with capital, with the expectation of a return on investment.

In developing the stakeholder saliency theory, Mitchell, Agle and Wood created a stakeholder typology that characterized the various types of stakeholders based on the presence of one, two or three of the attributes (power, legitimacy and urgency) being present (1997). Figure 10 depicts the final results of this typology.

Grossi went a step farther in the development of stakeholder theory by creating a framework for quantifying stakeholder saliency (2003). These models are shown here because they are utilized later in this thesis in order to determine the stakeholder saliency of the test and evaluation enterprise stakeholders.

In regards to *Power*, Frooman describes methods stakeholders utilize to exert their power on an enterprise by controlling the resources required to deliver value by either withholding resources or attaching usage constraints on those resources (1999). Grossi used the ideas presented by Frooman to develop a framework for quantifying a stakeholder's power factor based on their coercive, utilitarian, and symbolic attributes, which is shown in Appendix C, Table 21 (2003). In regards to *Urgency*, Grossi renamed this attribute to *Criticality* and created a methodology for determining a stakeholder's criticality by measuring their urgency and importance, which is depicted in Appendix C, Table 22 (2003). In regards to *Legitimacy*, Grossi's framework is depicted in Appendix C, Table 23 (2003).

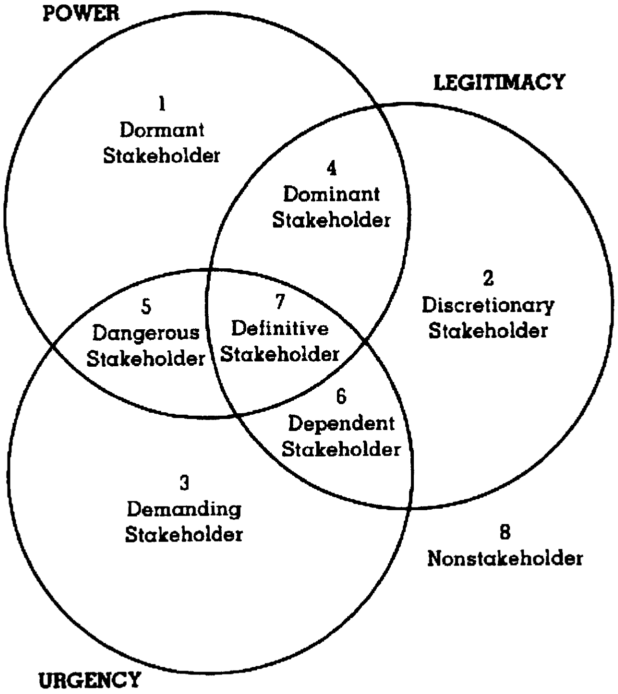


Figure 10 – Stakeholder Typology: One, Two or Three Attributes Present (Mitchell, Agle and Wood 1997)

The last step in determining the stakeholder saliency per the framework developed by Grossi is to combine the *Power*, *Criticality* and *Legitimacy* in order to determine the Stakeholder Saliency Index (SSI), which provides an index score based on a maximum of 130 (2003); there is also a Normalized Stakeholder Saliency Index (NSSI) that normalizes this score to a maximum of 100 (Grossi 2003).

$$SSI = \frac{\sqrt{3}}{4}(Power \times Legitimacy + Power \times Criticality + Legitimacy \times Criticality)$$

$$NSSI = \frac{3}{4}(Power \times Legitimacy + Power \times Criticality + Legitimacy \times Criticality)$$

The enterprise stakeholder model depicted in Figure 9 is representative of the DoD test and evaluation enterprise because it provides a holistic framework that accounts for stakeholder perspectives. These perspectives and stakeholder values provide insights that potentially identify underperforming areas on the enterprise that need to be changed. The DoD test and evaluation enterprise serves the purpose of verifying and validating the defense systems that are developed and acquired for the US warfighter. From a system perspective, the stakeholders are the components that make up the system and individually need to be understood in order conduct a holistic evaluation of the enterprise. This is more relative than taking a shareholder only perspective, which is representative of some commercial companies, and it is not representative of a holistic approach because it has a tendency of being short-sided leading to long term negative impact on the enterprise.

2.10 – Chapter Summary

The relevant literature for this research was reviewed in this chapter. Overviews of unmanned systems, defense acquisitions, systems and systems of systems, test and evaluation and decision support systems. Also, relevant material was reviewed in regards of value delivery to stakeholders of an enterprise.

Additionally, this chapter addressed the following strategic research question.

- How is test and evaluation from a system perspective different than that of systems of systems?

Basically, systems testing involve verification and validation against system requirements and is generally possible. SoS T&E is more challenging due to difficulty in synchronizing the moving parts across multiple systems.

(THIS PAGE INTENTIONALLY LEFT BLANK)

Chapter 3 – T&E SoS Stakeholder Analysis

3.0 – Opening Remarks

The purpose of this chapter is to answer the following research questions that were covered in Chapter 1:

- Who are the primary stakeholders of the test and evaluation enterprise?
- What are primary stakeholder values towards unmanned autonomous systems of systems (UASoS) testing?
- What are primary challenges to UASoS test and evaluation?

In anserwring these research questions, the strategic value definition can be generated for the utilization of *PATFrame* as a planning tool for UASoS test and evalutation.

The material presented in this chapter will step through a description of the enterprise that is being studied / analyzed. Also, the stakeholders are identified and task descriptions are provided for each stakeholder. Next, the results of stakeholder interviews are presented that provide stakeholder primary values towards unmanned systems testing. These values are important because they will feed into the development of the value proposition for the *PATFrame* DSS.

3.1 – Enterprise Description

Before proceding, it is important to distinguish between product and service enterprises. In general, a product enterprise can be considered as one that utilizes lean principles such as six sigma, total quality management and waste minimization to mass produce large quantities of a product into the market while delivering value to the stakeholders. Toyota car manufacturing can be thought of as a representative of a product enterprise (Womack et al. 1990). A service enterprise depends more on people, process and products to deliver value to the stakeholders as defined by Tien (2008). The DoD Test and Evaluation enterprise is a service enterprise that mitigates the risk within a systems of systems in order to deliver a capability to the end user (aka, the warfighter) via its people, processes and products. The people are professionally trained in doing test and evaluation; the processes are specific to mitigating risk via verification and validation; and the products are specific to T&E.

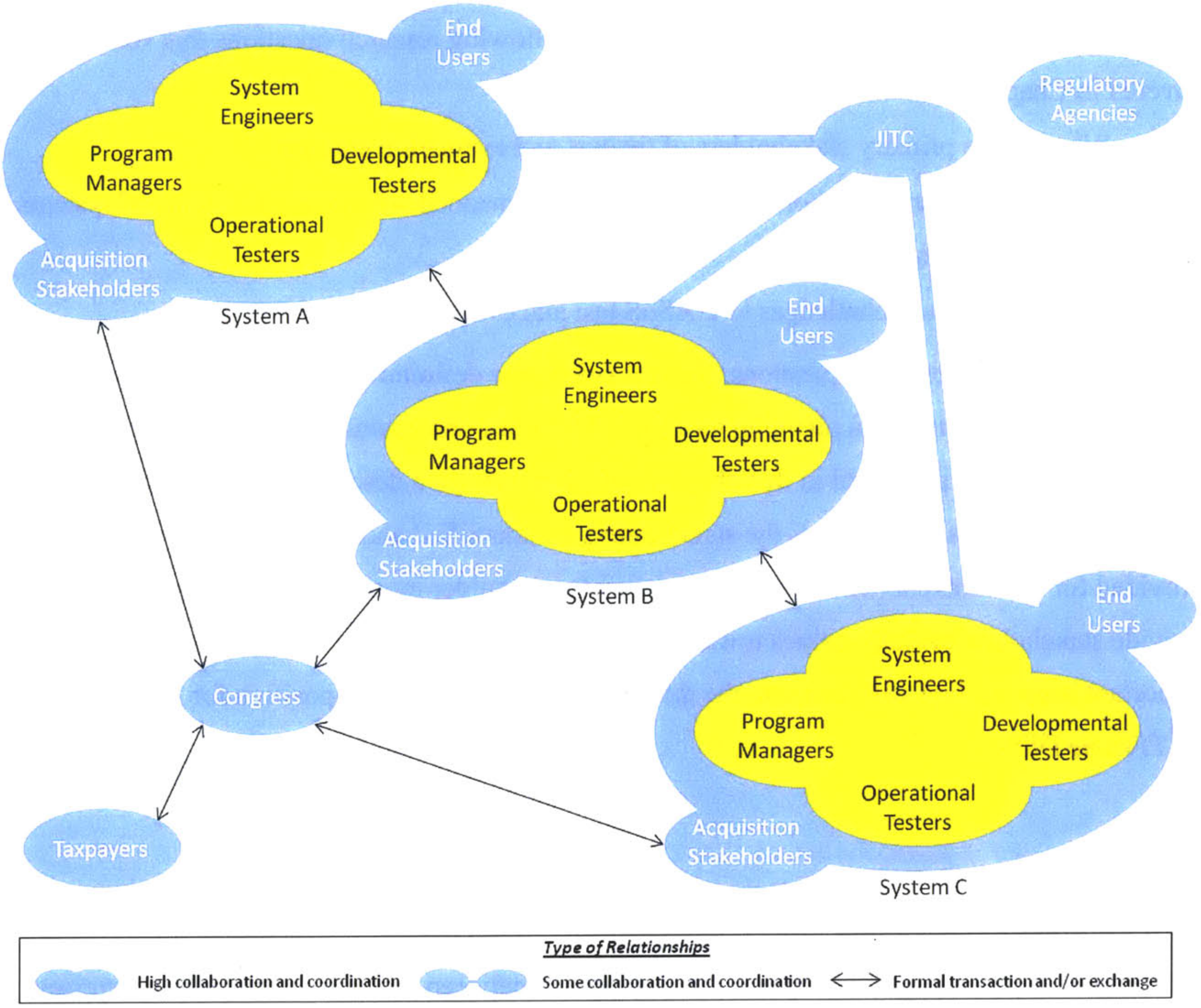


Figure 11 – Systems of Systems Test and Evaluation Stakeholder Water Drop Model

Figure 11 represents a notional systems of systems test and evaluation water drop model in the format developed by Grossi (2003). Each system has both external and internal stakeholders. The external stakeholders (Taxpayers, Congress, Acquisition Stakeholders, End Users and representatives from the Joint Interoperability Test Command (JITC)) are shown with white font and represent entities that are larger than the constituent system itself. The internal stakeholders (Program Managers, Systems Engineers, Developmental Testers and Operational

Testers) are shown with black font and represent key representative members of the constituent system who have the most impact on the test and evaluation of a constituent system.

Figure 12 shows an example of an Acknowledged SoS, as defined in Chapter 2 that has elements undergoing test and evaluation. This is representative of the Air Force systems that comprise an intelligence, surveillance and reconnaissance systems of systems (ISR SoS). Some of the constituent systems of the ISR SoS are the Global Hawk, Global Hawk Mission Control Element (MCE) and the USAF Distributed Ground System (DCGS). The Global Hawk unmanned aerospace system (UAS) is a constituent system that flies and collects user requested ISR data of a target, which originates from the MCE. This imagery is captured by the Global Hawk UAS and then provided to the user network that requested the imagery for analysis.

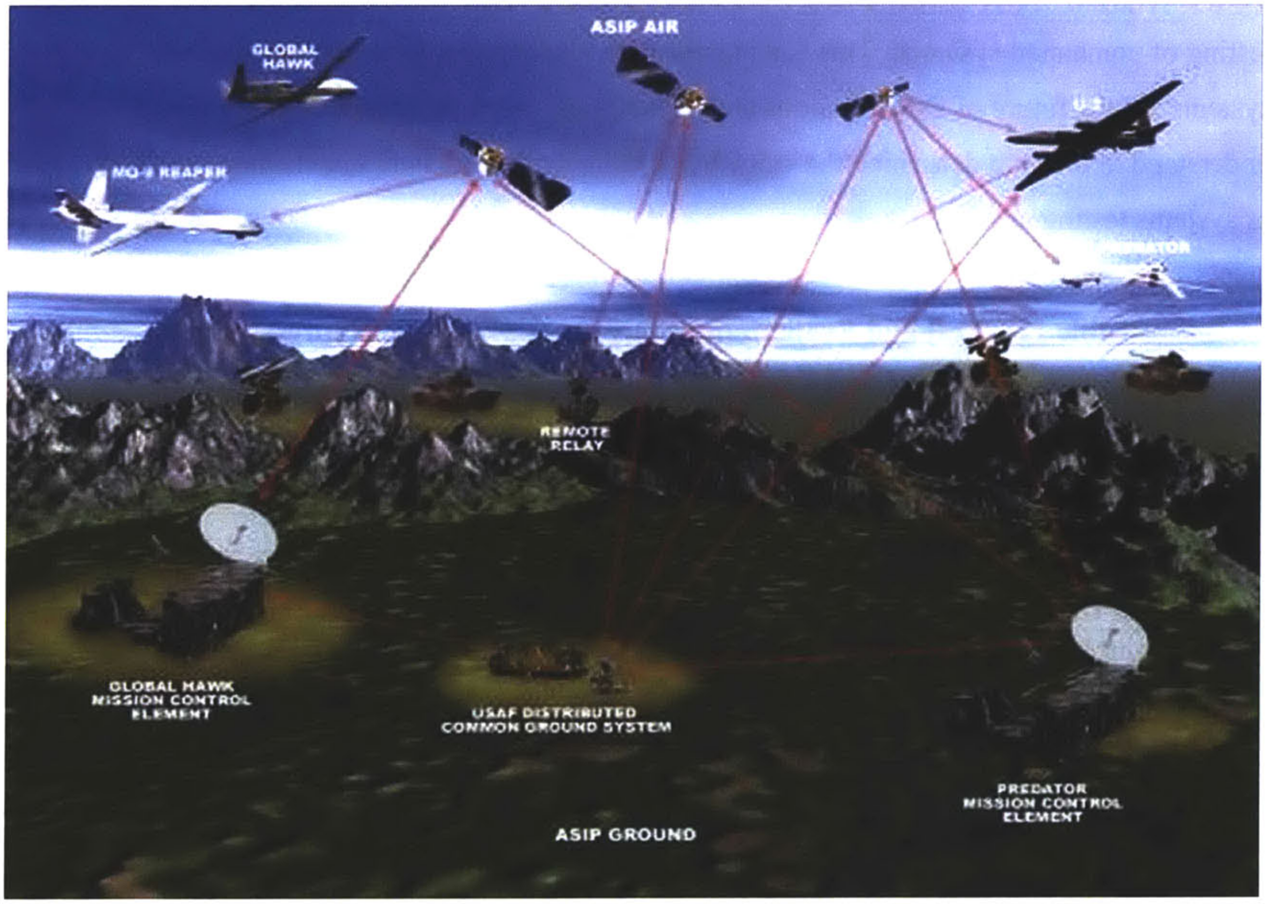


Figure 12 – US Air Force Intelligence, Surveillance and Reconnaissance Systems of Systems (Maddocks 2010)

Imbedded in this ISR SoS are the stakeholder relationships that are shown in Figure 11. Each constituent system in the SoS is an individually executed acquisition program that must properly interface with the other constituent system of the SoS and function properly without any undesired emergent behaviors that could negatively impact the intended capability of the SoS. In the case of the SoS shown in Figure 12, all constituent systems of the ISR SoS are tested by the internal stakeholders of that system in order to ensure that all interfaces work as designed in order to verify the design of the constituent system and validate the intended capability of the SoS.

3.2 – Stakeholder Identification

Table 11 shows the representatives that have been identified as stakeholders within the T&E enterprise. Select stakeholders were interviewed in order to determine the value for current testing of unmanned systems. This is a representative example to consider because unmanned systems are the future of DoD missions and capabilities. Also, this value is important to understand in order to determine the value expectations of future unmanned autonomous systems of systems testing.

Table 11 – Test and Evaluation Enterprise Stakeholder Representatives

Test and Evaluation Enterprise Stakeholders
Operational Testers
Developmental Testers (Government and Contractor)
Program Managers (Government and Contractor)
Systems Engineers (Government and Contractor)
Acquisition (Personnel w/ High Level of Interest in Test and Evaluation Results)
End User (Warfighters who Employ the System)
Joint Interoperability Test Command (JITC)
Congress
Taxpayers
Regulatory Authorities

Operational Testers: The operational testers conduct operational assessments on systems early in the acquisition cycle in order to gauge the operational utility early in the life cycle as well as examining the operational capabilities of systems that have completed developmental test. These types of tests fall under the guise of Operational Test and Evaluation (OT&E). Also, operational testers are responsible for the overall validation of the constituent system's operation within a SoS by evaluating interfaces and the delivery of the stated capabilities to the user. Each military branch of the DoD has an operational test organization that performs OT&E. In particular, the Air Force Operational Test and Evaluation Center (AFOTEC) conducts operational testing for the USAF.

Developmental Testers: The developmental testers are responsible for taking the system that is under development and seeing that it is tested in accordance to the constituent system test plan, which is the overall verification of the system requirements. Each constituent system of a SoS has a test plan known as the Test and Evaluation Master Plan (TEMP). The TEMP is the document that lays out the tests for a system over the course of its life cycle. Also, the developmental testers play a role in the systems engineering process by verifying the system meets the system requirements specified by the user in the design of the full component system.

Program Managers: There are two subgroups in this stakeholder group. One is the Government Program Manager and the other is the Contractor Program Manager. The role of the system program managers is to ensure the system within the SoS are developed and delivered on time, at cost and on schedule. This will ensure that test schedule is not delayed because of component unavailability, which is a challenge at the SoS level because of asymmetric schedules of constituent systems (Dahman et al. 2010).

Systems Engineers: There are two subgroups amongst the Systems Engineering stakeholder group in a similar fashion to that of Program Managers, which is represented by the Government and Contractor. The System Engineer is responsible for the total integration of the system that is being developed and follows the general steps of the system engineering process: develop requirements; allocate the system requirements; design the elements of the system; build, integrate and test the elements of the system; and conduct full system verification & validation. The role of the systems engineer is also important to the SoS because of the possibility of emergent behaviors as well as seeing that the constituent system interfaces appropriately with the SoS.

Acquisition Stakeholders: This group of stakeholders is at the Secretariat level and is represented by the Program Element Monitor (PEM). A PEM is considered the representative of the Strategic stakeholder due to his/her authority to influence the outcome of a component system of the SoS that is undergoing test and evaluation.

End User: The User represents the airmen, soldiers, sailors and marines that utilize the weapon systems of the DoD during the missions that are being performed both in peace and wartime operations.

Joint Interoperability Test Command (JITC): JITC's mission is to provide a full-range of agile and cost-effective test, evaluation, and certification services to support rapid acquisition and fielding of global net-centric warfighting capabilities (JITC 2010). JITC is considered a stakeholder because of the Network-centric focus of UASoS. Network centricity refers to the ability of the constituent members within the SoS to be electronically connected with each other in order to have clear and secure communications.

Congress: Members of Congress are considered stakeholders because they provide the political support for the constituent systems that make up the SoS undergoing test and evaluation.

Taxpayers: The taxpayer is a stakeholder because it is their money that provides funding for DoD test and evaluation as well as they are the ones the DoD protects.

Regulatory Authorities: The Regulatory Authorities are primarily government entities that oversee regulations that impact the way systems are utilized. An example of a US regulatory body would be the Federal Aviation Administration (FAA) and its role in developing the standards for how unmanned aerial vehicles will operate autonomously in US air space.

3.3 – Stakeholder Saliency

Grossi's stakeholder saliency index provides a framework for determining the relative importance of the stakeholders to the enterprise based on the evaluation of their power, legitimacy and criticality attributes (2003). Table 12 shows the stakeholder saliency index which identifies stakeholders that have the most influence over test and evaluation and is based on the author's experience as well as the interpretation of stakeholder interview results, which will be covered later in this chapter. The top five stakeholders are the Operational Testers, Developmental Tester, Program Managers, Systems Engineers and Strategic Level Stakeholders. It is not surprising that the Operational Testers are the highest ranking member of the test and evaluation enterprise. This is driven by the fact that the operational testers have a direct tie to the Director of Operational Test and Evaluation in the DoD organization structure, which can be seen in the Organizational View of the enterprise (Chapter 4).

Table 12 – Stakeholder Saliency Index

	Criticality Attribute			Power Attribute				Legitimacy Attribute				Saliency Index		
Stakeholder	Urgency	Importance	Criticality Average	Coercive	Utilitarian	Symbolic	Power Average	Pragmatic	Moral	Cognitive	Legitimacy Average	SSI	NSSI	Rank
Operational Testers	10	10	10.0	2	9	9	6.7	8	8	8	8.0	86.6	66.7	1
Developmental Testers	9	9	9.0	2	9	8	6.3	8	8	8	8.0	77.8	59.9	2
Program Managers	9	9	9.0	2	9	8	6.3	8	8	8	8.0	77.8	59.9	3
Systems Engineers	9	9	9.0	2	5	8	5.0	7	7	7	7.0	61.9	47.7	4
Acquisition Level	8	8	8.0	2	4	6	4.0	8	8	8	8.0	55.4	42.7	5
JITC	8	8	8.0	2	3	8	4.3	7	7	7	7.0	52.4	40.3	6
End User	6	6	6.0	2	6	5	4.3	6	6	6	6.0	38.1	29.3	7
Congress	7	7	7.0	2	4	7	4.3	5	5	5	5.0	37.7	29.0	8
Regulatory Authoriities	7	7	7.0	2	4	6	4.0	5	5	5	5.0	35.9	27.7	9
Taxpayers	7	7	7.0	2	3	7	4.0	4	4	4	4.0	31.2	24.0	10

3.4 – Stakeholder Interview Results

Stakeholder interviews were used in order to obtain values of the top five stakeholders indentified from the stakeholder saliency analysis. These values are important to understand because they form the foundation for determining how more rigorous test planning can increase delivered value to the test and evaluation enterprise for the test planning of unmanned autonomous systems of systems.

There are two types of values being addressed in these interviews. The first is "Relative Value Importance", which is an indication of overall "worth" to the stakeholder and is considered to be the stakeholder's ultimate measure of value to be achieved by the enterprise. The second is "Current Value Delivery", which is an assessment of how well the current enterprise construct is delivering value to the stakeholder and serves as a enterprise value performance indicator. Also, a 5 point scale, ranging from 1 to 5, was used in order to rate the "Relative Value Importance" and "Current Value Delivery" for each value area of the stakeholders. A 1 means failure, 2 represents poor performance, 3 is satisfactory performance, 4 is categorized as good performance and a 5 indicates excellent performance.

Figure 13 to Figure 18 show the key values identified by each of the stakeholders as well as the ratings for the relative value importance and current value delivery. All charts depict that the current value delivery is less than the relative value importance. This is important to keep in mind because if this is a challenge at the system level for unmanned systems then it will also be a challenge at the unmanned autonomous systems of systems level.

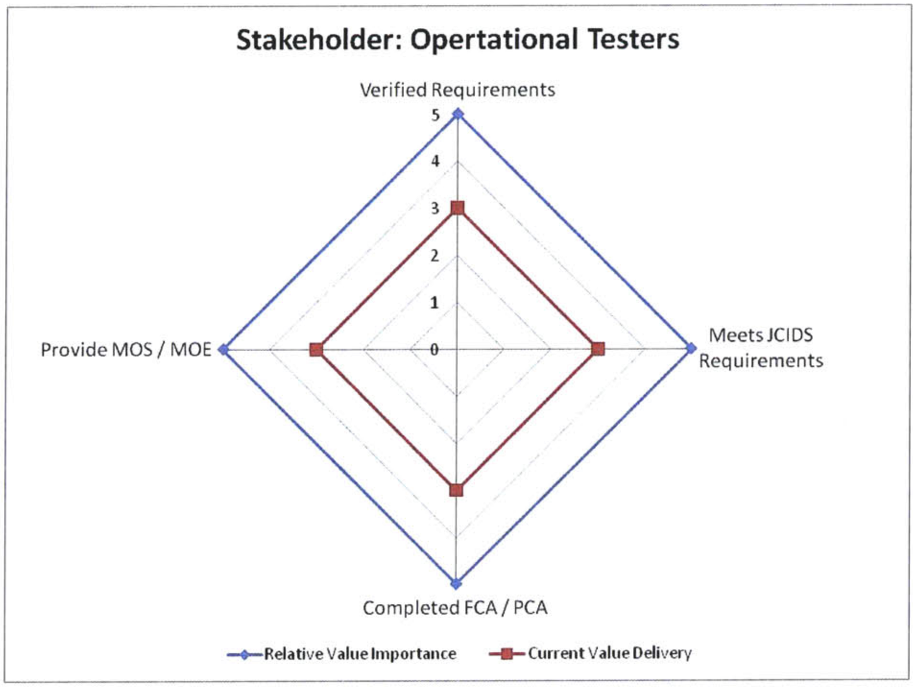


Figure 13 – Stakeholder Value for Operational Testers

Based on interviews, the operational testers have four stakeholder values (Figure 13) that need to be addressed. The first is "Verified Requirements", which represents the fact that a system should successfully verify all or most of the its specified requirements during developmental testing before entering initial operational testing. Secondly, the operational testers place value in the ability of the system to "Meet JCIDS Requirements", which is needed in order for the solvability of the system to be completely relized. This means the system needs to satisfy the materiel solutions criteria established by the warfighter. The third value identified in the interview process was a "Completed FCA/PCA", which calls for the system to have completed its required functional configuration audit[1] and physical configuration audits[2] before dedicated operational testing in order to provide a system that is representative of what will be delivered to the warfighter. The final value was "Provide MOS/MOE", which is the determination of adequate evaluations of measures of suitability (MOS) and measure of effectiveness (MOE) in order to allow for informed acquisition decisions into whether to buy the system or not. The "Relative Value Importanance" and "Current Value Delivery" were rated as a five and a three, respectively, for the four identified staekholder values by the researcher and are based on the interpretation of the stakeholder interview results. This indicates thats the T&E enterprise is currently not delivering the relative value desired by the operational test community and are challenges that need to be overcome in order for SoS level test and evaluation to deliver the value to the enterprise. There are some additional SoS T&E challenges that were identified by the OT stakeholder based on follow up conversations and are provided below (Maddocks 2010):

- Systems of systems have emergent behavior, which creates "unknown unknowns" and unpredictable behavior. Current planning tools are based on traditional system models, and don't adequately account for the unpredictable nature of complex systems.
- By definition, a system-of-systems is not managed under one roof. An SoS is a federation of systems. Traditional hierarchical management techniques are inadequate in an SoS environment.
- Programmatically, unpredictability leads to schedule slips and cost overruns. Moreover, the lack of control over other systems within an SoS, schedules among the federated members get out of synch, which in turn leads to interoperability problems.

---

[1] A functional configuration audit (FCA) is defined as "the formal examinations of functional characteristics of a configuration item, or system to verify that the item has achieved the requirements specified in its functional and/or allocated configuration documentation". (OUSD/AT&L, MIL HDBK 61B, "Configuration Management Guidance", 2002).

[2] A physical configuration audit (PCA) is defined as "the formal examination of the 'as-built' configuration of a configuration item against its technical documentation to establish or verify the configuration item's product baseline". (OUSD/AT&L, MIL HDBK 61B, "Configuration Management Guidance", 2002).

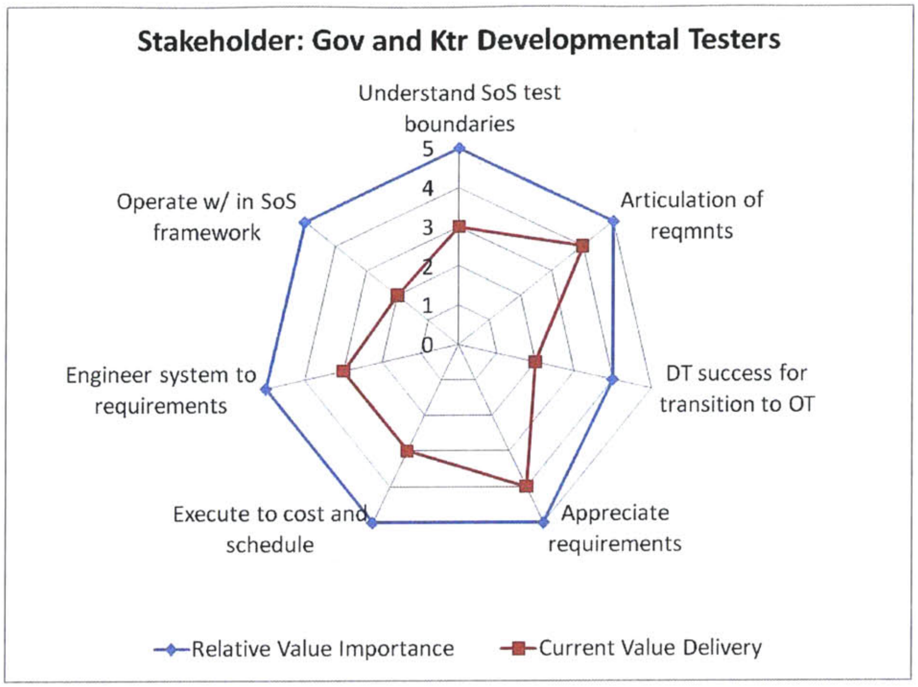


Figure 14 – Stakeholder Value for Developmental Testers

Figure 14 depicts the stakeholder values for both the government and contractor development testers. Overall, there were seven values identified during stakeholder interviews. For the sake of brevity, this evaluation will focus on what the researcher considers the top three topics of value exchange for the developmental test stakeholders and is motivated because of their importance to the outcome of SoS testing. The first is for the system to "Operate with in a SoS Framework", which correlates to the ability of the constituent system to verify it meets the requirements of interfacing with the other SoS components. This stakeholder value received a five for its "Relative Value Importance" and a two for its "Current Value Delivery". The second DT stakeholder value of importance is to "Understand SoS Test Boundaries", which focuses on the importance of the clearly defining the test boundaries in order to identify roles and responsibilties for the parties accountable for the various constituent systems. This stakeholder value received a five for its "Relative Value Importance" and a three for its "Current Value Delivery". The third DT stakeholder value of importance is the ability to "Execute To Cost and Schedule", which simply focuses on the ability of the developmental testing to be completed within the available resources that have been allocated to complete the task. One thing that might cause the system to exhaust its resources is unknown and unanticipated emergent behaviors that could arise once the SoS constitient system is integrated and tested as part of the total SoS. All three of the DT values are challenges that are important for SoS testing to address in order to be able to predict the potential for emergent behaviors in order to be able to test within the available resources (i.e., cost and schedule).

Figure 15 – Stakeholder Value for Contractor Program Managers

Figure 15 depicts the stakeholder values for contractor program managers (PM). The first is for the "System Built to Specification", which correlates to the ability of the contractor to deliver a system that meets the system requirements that have been developed. This stakeholder value received a five for its "Relative Value Importance" and a four for its "Current Value Delivery". The second stakeholder value of importance is to achieve "Successful SoS Integration", which implies the need in understanding the SoS interfaces of the constituent system. This stakeholder value received a five for its "Relative Value Importance" and a four for its "Current Value Delivery". The third contractor PM stakeholder value of importance is the ability to "Understand SoS Interfaces", which correlates to the ability of the constituent system contractor to comprehend the interface requirements with the other SoS components. A value of five was assessed for its "Relative Value Importance" and "Current Value Delivery" received a three. The takeaway here is to meet the challenge of ensuring the constituent system of the SoS is built to specifications and has the proper interfaces that will enable successful integration with the other elements of the SoS.

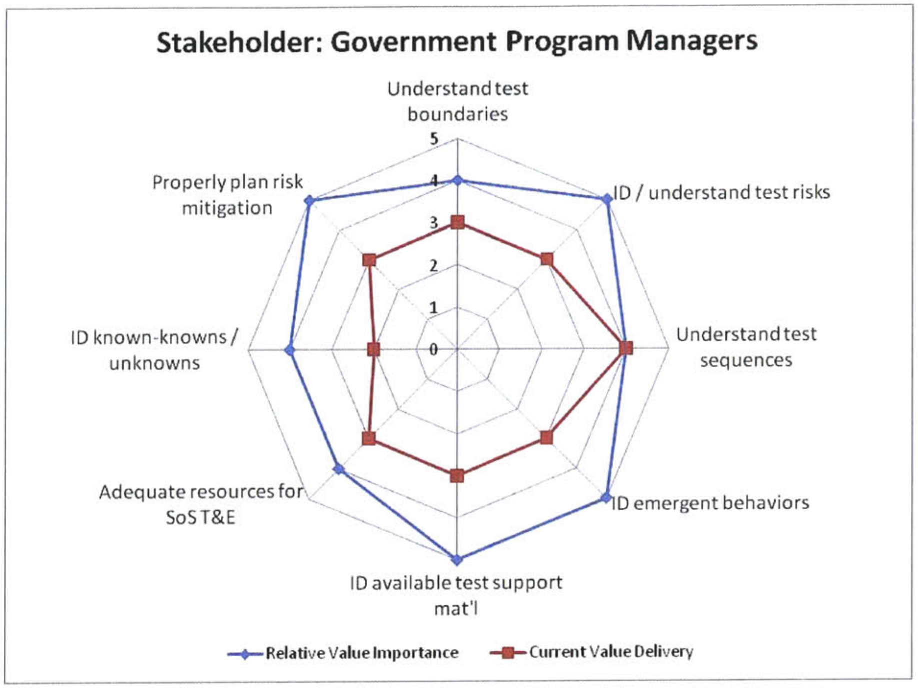


Figure 16 – Stakeholder Value for Government Program Managers

Figure 16 depicts the stakeholder values for government program managers (PM). Overall, there were eight values identified during stakeholder interviews. The government PM values that received a five for "Relative Value Importance" will be further examined because they are the most important values for this stakeholder. The first value is the "Identification and Understanding of Test Risks", which calls for a PM to have situational awareness of the risks associated with testing the constient system within the SoS framework. This value was assigned a three for "Current Value Delivery". The second value is the "Identification of Emergent Behaviors", which calls for the ability to understand the emergent behaviors that could arise when the costituent systems of the SoS interface with each other. This value was assigned a three for "Current Value Delivery". The third value for government PM is to be able to "Identify Available Test Support Materiel", which means the PM needs to identify the entities that will support the testing of the constituent system in order to allow for adequate lead time for their acquisition. The "Current Value Delivery" for this stakeholder value was assigned a three. The last value is the ability of the government PM to "Properly Plan for Risk Mitigation", which calls for the ability of the PM to be able to develop proper risk mitigation plans for the constituent system. In a similar fashion as the other values, the "Current Value Delivery" was assigned a three. The takeaway here points to the challenge of identifying emergent behaviors and how they can impact the availability of test support material; scoping & understanding of test risks; and developing risk mitigation plans.

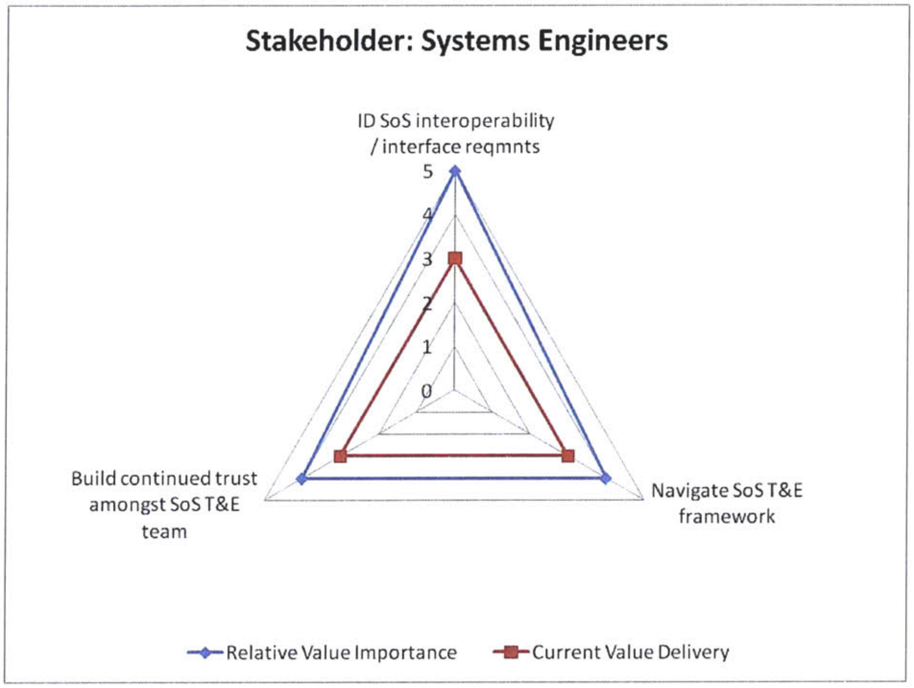


Figure 17 – Stakeholder Value for Systems Engineers

Figure 17 depicts the stakeholder values for systems engineers. The first is to "Identify SoS Interoperability and Interface Requirement", which requires the understanding of how the constituent system fits into the SoS as well as communicates with other systems in the SoS. This stakeholder value received a five for its "Relative Value Importance" and a three for its "Current Value Delivery". The second stakeholder value of importance is to be able to "Navigate the SoS T&E Framework", which implies the ability to understand the channels of communication amongst the SoS constituent component systems.. This stakeholder value received a four for its "Relative Value Importance" and a three for its "Current Value Delivery". The third value of importance to the SE is the ability to "Build Continued Trust Amongst the SoS T&E Team", which highlights the human communication aspect of SoS T&E. If proper and continued communication does not occur within the SoS, then it is possible for the overall SoS T&E

objectives to not be accomplished. This value received a four for "Relative Value Importance" and its "Current Value Delivery" received a three

There are several challenges that can be identified as a result from the values identified by the systems engineers. The first is shared by other stakeholders and that is the identification of interoperability and interface requirements of the constituent system within the SoS. The second challenge stems from builiding continued trust amongst the SoS T&E team, which is important because it introduces and emphasizes the human relationship aspect of the SoS test and evaluation. These relationships between the personnel running the SoS constituent systems must have continued communications as well as an understanding of the T&E framework for the SoS in order to be successful whether a constiuent system is manned or unmanned.

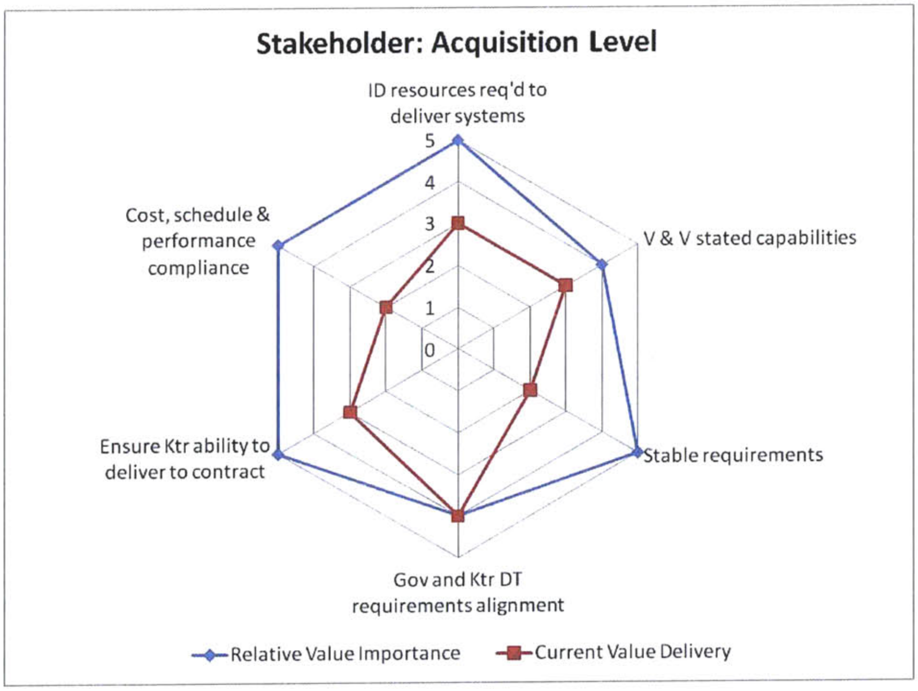


Figure 18 – Stakeholder Value for Acquisition Level Stakeholders

Figure 18 depicts the values for the strategic level acquisition stakeholders. Two of these values will be covered because they have the largest varience between the "Relative Value Importance" and the "Current Value Delivery". Both of these values were given a five for "Relative Value Importance" and a two for "Current Value Delivery". The first is the value of "Cost, Schedule and Performance Compliance" for the system that is undergoing test. This is important because the Acquisition Level stakeholders need to be able to understand if a system is not able to stay within the specified cost, schedule and performance boundaries then they will need to take action in order to provide a solution to the issue that is being experienced. The second value is that of "Stable Requirements", which addresses the fluid nature of how requirements changes can possibly impact the ability of a system to complete test and evaluation.

A limitation that was identified during the interview with the stakeholder was that the focus at the Acquisition Level into T&E is not as high as it should be. Most focus at this the Acquisition Level is on the cost, schedule and performance aspects of the program. T&E focus is left primarily upto the program manager and the test team to workout. This stakeholder becomes more involved when issues with test and evalaution are elevated to the attention to the Acquisition Level stakeholders. The two stakeholder values chosen for further consideration are important because, based on experience, they are two areas of a constituent system that can lead to potential negative involvement from the Acquisition Level stakeholders. This is driven by the stability of requirements as well as the compliance of cost, schedule and performance of the constituent system within the SoS.

3.5 – Stakeholder Interview Validity

Now that all stakeholder interview results have been presented, it is important to discuss data validity due to the fact the data were obtained based on experimental data collection as a result of interviews. It is important to cover this topic due to the possibility of internal and external validity issues with stakeholder interview data.

Internal validity can be questioned due to the possibility that the conclusions drawn from experimental results may not accurately reflect what has gone on in the experiment itself (Babbie 2004). Also, it addresses the question of, "was the study sensitive enough to detect a causal relationship" (Isaac & Michael 1997)? Simply put, internal validity deals with the accuracy of the data. One tactic that was exercised in order to maintain internal validity of the experimental data was to have a direct discussion with the interviewees either in person or by phone in order to walk them through the survey questions. This methodology allowed for open discussions that helped clear up ambiguities in regards to expectations. Internal validity could have been increased by conducting all interviews face to face. This would allow for the interviewer to guide discussions with the interviewee based on physical reactions and impulses that occur during conversation.

External validity relates to the generalizability of experimental findings to the "real" world. This is true even if the results of an experiment are an accurate gauge of what happened during the experiment; do they really tell us anything about life in the wilds of society (Babbie 2004)? Also, external invalidity addresses the question of, "can the cause and effect noted in the study be generalized across individuals, settings and occasions" (Isaac & Michael 1997)? There are three potential aspects of external validity that may apply to the data set obtained in this research. First, were the research questions posed thorough enough to gather accurate data that reflects the generalized behavior of systems of systems testing? This is a valid concern because the interviews were conducted primarily with members of the Air Force. Interviews with stakeholder representatives from other service branches could possibly increase the external validity of the data set gathered. Second, were all of the relevant stakeholders interviewed? All of the stakeholders shown in Figure 11 were not interviewed. However, the five stakeholders with the highest saliency index scores shown in Table 12 were interviewed. Four out of five of these interviewees were internal stakeholders, which represents those who are the most familiar with test planning of a constituent system in a SoS. External validity could be increased by interviewing other representative stakeholders vice using individual experiences from working in the USAF test and evaluation arena.

3.6 – Chapter Summary

As stated before, this chapter addressed three strategic research questions. Condensed answers are provided per question in order to provide a brief summary.

- Who are the primary stakeholders of the test and evaluation enterprise?

The identified stakeholders are represented by external and internal groups. The external stakeholders are considered to be Taxpayers, Congress, Acquisition Level, End Users and the representatives from the Joint Interoperability Test Command (JITC). The internal stakeholders are considered to be Program Managers, Systems Engineers, Developmental Testers and Operational Testers.

- What are the primary stakeholder values toward unmanned autonomous systems of systems testing?

Table 13 provides a summary of the stakeholder values that have been deemed the most important based on a stakeholder interviews and saliency analysis. It can be seen that there is a difference between the current delivery and relative importance of the stakeholder values. The gaps between current delivery and relative importance can possibly be closed utilizing the *PATFrame* decision support system as described by Valerdi et al. (2008).

- What are primary challenges to UASoS test and evaluation?

Stakeholder interviews provided the source of information in order to answer this question. In summary, the stakeholders pointed out the following challenges: ensure smooth transition from DT to OT for constituent members of the SoS; have the ability to predict potential for emergent behaviors (both good and bad) and be able to test these emergent behaviors within the available resources; be able to build the constituent systems to design specifications and understand the required SoS interfaces; be able to scope and understand the test risks and develop risk mitigation plans; build and establish continued trust amongst the SoS team members; and ensure stability of SoS requirements in order to not extend required time for testing.

Table 13 – Summary of Important Stakeholder Values

No	Stakeholder	Value	Relative Importance	Current Delivery
1	OT	Verified Requirements	5	3
2	OT	Meets JCIDS Requirements	5	3
3	OT	Completed FCA / PCA	5	3
4	OT	Provide MOS / MOE	5	3
5	DT (Gov & Ktr)	Understand SoS Test Boundaries	5	3
6	DT (Gov & Ktr)	Operate within SoS framework	5	2
7	DT (Gov & Ktr)	Execute to cost and schedule	5	3
8	PM (Ktr)	System built to specification	5	4
9	PM (Ktr)	Successful SoS integration	5	4
10	PM (Ktr)	Understand SoS interfaces	5	3
11	PM (Gov)	ID & understand test risks	5	3
12	PM (Gov)	ID emergent behaviors	5	3
13	PM (Gov)	ID available test support materiel	5	3
14	PM (Gov)	Properly plan risk mitigation	5	3
15	SE	Id SoS interoperability & interface requirements	5	3
16	SE	Navigate SoS T&E framework	4	3
17	SE	Build continued trust amongst SoS T&E team	4	3
18	Acquisition Level	Cost, schedule and performance compliance	5	2
19	Acquisition Level	Stable requirements	5	2

(THIS PAGE INTENTIONALLY LEFT BLANK)

Chapter 4 – "As-Is" Enterprise Architecture Analysis of T&E SoS

4.0 – Opening Remarks

This chapter will look at the T&E enterprise through the Enterprise Architecture views and will address the following research questions from Chapter 1:

- What are primary challenges to UASoS test and evaluation?
- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

A partial answer to the first question was provided in the previous chapter. The material in this chapter will be considered an addendum to the findings from Chapter 3 and will take a holistic view of the T&E enterprise and identify additional challenges that will need to be overcome in order to provide value to the stakeholders. Also, this chapter will provide an answer to the second question from a strategic perspective. Chapter 5 will be utilized to complete the answer for the second question at the tactical level.

4.1 – Service and Product Views

The service view investigates the "service(s) delivered and or supplied by the enterprise, including in support of products" and the product view looks at "products developed by the enterprise; key platforms; modular versus integral architectures, etc" (Rhodes, Ross and Nightingale 2009).

For the sake of this research, the Service and Product views are being combined because the delivery by the Test and Evaluation enterprise is the verification and validation of a capability that is delivered in the construct of a system of systems via the DoD acquisition process. Test and Evaluation in the simplest terms can be defined in its two parts. Test is a systematic means of collecting data which can be analyzed and used to formulate statements regarding the performance of a component, system or [system of systems] concept that is within certain limits of error (Testing produces the Product). Evaluation is the process by which one examines the test data and statements, as well as any other influencing factors, to arrive at a judgment of the significance or worth of the component, system or [systems of systems] concept (Giadrosich 1995) (Evaluation is the Service).

Another perspective of the T&E service stems from DoD 5000.02 (Service and Product). "The fundamental purpose of T&E is to provide knowledge to assist in managing the risks involved in developing, producing, operating, and sustaining systems and capabilities. T&E measures progress in both system and capability development. T&E provides knowledge of system capabilities and limitations to the acquisition community for use in improving the system performance, and the user community for optimizing system use in operations. T&E expertise must be brought to bear at the beginning of the system life cycle to provide earlier learning about the strengths and weaknesses of the system under development. The goal is early identification of technical, operational, and system deficiencies, so that appropriate and timely corrective actions can be developed prior to fielding" (OUSD(AT&L) 2008a).

There are two tangible Products that depict how the T&E service is delivered in the T&E enterprise. The first is the Test and Evaluation Strategy (TES), which is developed in support of Milestone A (see Figure 6) decisions of an acquisition system as a result of the development of the Initial Capabilities Document (ICD). The second document is the Test and Evaluation Master Plan (TEMP), which is developed for Milestone B and C decisions (see Figure 6) in the acquisition cycle and corresponds to the Capabilities Development Document (CDD) and Capabilities Production Document (CPD), respectively.

4.2 – Organization View

The organization view, as defined in Chapter 2, examines "the organizational structure of the enterprise of the enterprise as well as relationships, culture, behaviors and boundaries between individuals, teams and organizations" (Rhodes, Ross and Nightingale 2009).

There will be two organizational levels considered for the DoD Test & Evaluation enterprise in this analysis. The first will be the DoD level and the second will be at the US Air Force service component level. The DoD level is shown in Figure 19, which depicts the three primary players in the "As-Is" DoD T&E enterprise and consists of three organizations at the DoD level: Operational Test and Evaluation (OT&E); Developmental Test and Evaluation (DT&E); and Test Resource Management Center (TRMC).

Each Organization has a different mission in the overall construct of the DoD T&E Enterprise:

- Operational Test and Evaluation: The Director, Operational Test & Evaluation (DOT&E) is the principal staff assistant and senior advisor to the Secretary of Defense on operational test and evaluation (OT&E) in the Department of Defense. DOT&E is responsible for issuing DoD OT&E policy and procedures; reviewing and analyzing the results of OT&E conducted for each major DoD acquisition program; providing independent assessments to SecDef, the Under Secretary of Defense for Acquisition, Technology and Logistics (USD(AT&L)), and Congress making budgetary and financial recommendations to the SecDef regarding OT&E; and oversight to ensure OT&E for major DoD acquisition programs is adequate to confirm operational effectiveness and suitability of the defense system in combat use (DoD 2010).

- Developmental Test and Evaluation: Under Title 10, United States Code, the DDT&E is the principal advisor to the Secretary of Defense and the Under Secretary of Defense for Acquisition, Technology and Logistics on developmental test and evaluation in the DoD. The responsibilities of DT&E include: program oversight, policy and guidance, test plan approval (shared responsibility with OT&E), advocate for the acquisition T&E workforce; serve as a component T&E capability; and provide an annual report to Congress (Dipetto 2010).

- Test Resource Management Center: The Director of the TRMC is responsible for the planning and assessment of the adequacy of the Major Range and Test Facility Base (MRTFB) to provide adequate testing in support of development, acquisition, fielding, and sustainment of defense systems. The TRMC also maintains an awareness of other test and evaluation (T&E) facilities and resources, within and outside the Department, and their impact on DoD requirements (DoD 2004). There are also other areas of responsibility for the TRMC that exist, but one of them specifically applies to, which is to administer the Central Test and Evaluation Investment Program and the DoD Test and Evaluation Science and Technology Program.

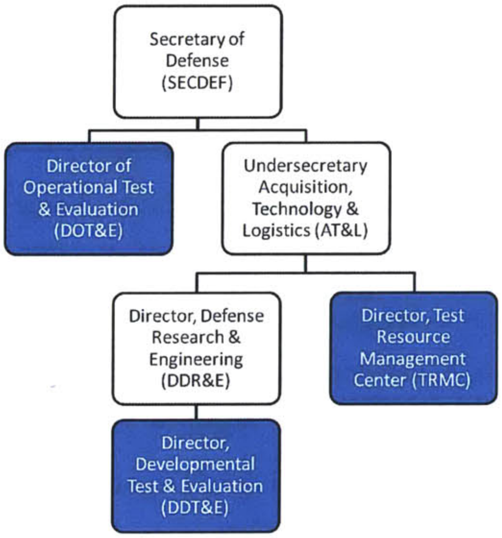


Figure 19 – Department of Defense Test and Evaluation Enterprise

Figure 19 shows there are representatives for DT, OT and TRMC at the DoD level of the T&E enterprise. This is important because this allows for all TES and TEMP documentation to be reviewed and approved by all three representatives at the DoD level. DOT&E is responsible for approving the OT specific material of the TES or TEMP; DDT&E reviews and signs off on the DT portion of the TES / TEMP; and TRMC reviews the resource requirements specified by the TES / TEMP.

As mentioned, there is a second lower level in the DoD T&E enterprise that resides within each branch of the military. Each service has both developmental and operational testing components reflecting the differentiation between the roles of the DT and OT. The Air Force and Navy have disparate organizations that are primarily responsible for the DT and OT missions. The Air Force's DT efforts take place under the auspices of Air Force Materiel Command (AFMC) and OT efforts take place under the Air Force Operational Test and Evaluation Center (AFOTEC). The Navy's DT efforts primarily take place under the naval air, sea and space commands: Naval Air Systems Command (NAVAIR), Naval Sea Systems Command (NAVSEA) and Space and Naval Warfare Systems Command (SPAWAR). The Navy's OT agency is the Operational Test and Evaluation Force (OPTEVFOR). The Army has both the DT and OT functions combined in the Army Test and Evaluation Command (ATEC) and has one commander providing oversight to both functions.

In order to provide a specific example, this thesis will focus mainly on the secondary level of the T&E Enterprise that resides in the US Air Force with an emphasis on unmanned systems. As mentioned before, the Air Force consists of separate organizations that perform the missions of DT and OT throughout the life-cycle of an acquisition system (Figure 6).

The DT mission is performed primarily by the US Air Force Materiel Command (AFMC), which develops, acquires and sustains the aerospace power needed to defend the United States and its interests for today and tomorrow. This is accomplished through management, research, acquisition, development, testing and maintenance of existing and future weapons systems and their components. (AFMC Services 2010) AFMC is headquartered at Wright Patterson AFB in Dayton, OH and consists of Depot and Maintenance Facilities, Product Centers along with Test and Evaluation Centers that are located in various locations within the Continental United States (CONUS). Air Force flight testing of unmanned systems primarily takes place at Edwards AFB, CA. Figure 20 depicts the geographical locations of the bases that fall under the auspices of AFMC.

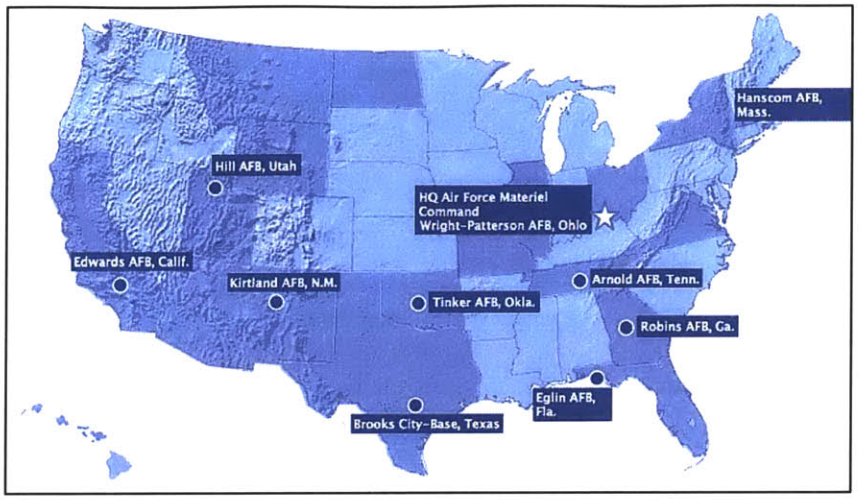


Figure 20 – US Air Force Materiel Command Operating Locations (AFMC Services 2010)

The OT mission is performed primarily by the US Air Force Operational Test and Evaluation Center (AFOTEC), which is headquartered at Kirtland AFB in Albuquerque, NM and has various locations at other CONUS installations, as shown in Figure 21. AFOTEC tests and evaluates new weapon systems in realistic battlespace environments to provide decision makers a range of accurate; balanced; and timely assessments of effectiveness; suitability; and mission capability. (AFOTEC 2010)

Two observations can be made by the T&E enterprise Organization View that potentially impact unmanned autonomous systems of systems (UASoS) testing. First, the high level organization of the DoD has insight into the three entities that influence control over the T&E. This is a positive because DT and OT as well as resources are all considered when final approval of the test strategies is underway. Second, the T&E Organization view demonstrates the amount of geographic separation between the various organizations that make up the Air Force component of the DoD T&E enterprise, which presents the potential challenge and/or need of being able to effectively communicate with other parties in a SoS.

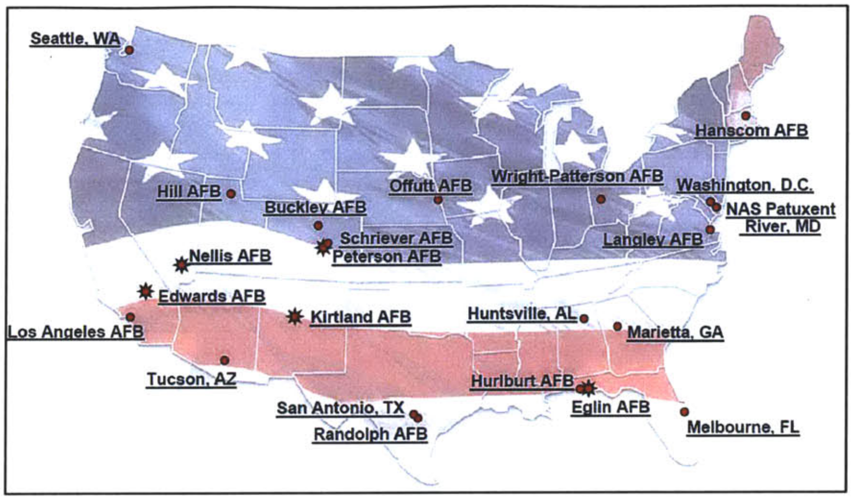


Figure 21 – US Air Force Operational Test and Evaluation Center Locations (AFCEA 2010)

4.3 – Policy and Strategy Views

The policy view examines "the external regulatory, political and societal environments in which the enterprise operates" and the strategy view looks at the "strategic goals, vision, and direction of the enterprise including the business model; enterprise objectives and objectives" (Rhodes, Ross and Nightingale 2009).

Several key pieces of policy impact and drive the T&E strategy of systems and SoS. The first is DoD 5000.02, which institutes the policy of integrated developmental testing and operational testing (IDT/OT) (OUSD(AT&L) 2008a). The primary purpose of IDT/OT is to combine operational testing into the developmental testing sequence as early as possible. This helps to place an operational focus on the testing of a system or systems of systems early in the acquisition cycle. Also, this helps to descope the amount of data that will be required to be captured during OT due to the potential reuse of data that was captured during DT.

Second, the Weapons Systems Acquisition Reform Act (WSARA) of 2009 that became public law on 22 May 2009 impacts test and evaluation (OUSD(AT&L) 2008b). T&E is impacted because WSARA established the role of Director, Developmental Test and Evaluation (DDT&E) in order to ensure that all aspects of T&E had coverage at the OSD level (see Figure 19). Specific roles of the new DDT&E position are to review and approve DT&E plans in the TES and TEMP for major defense acquisition programs (MDAPs) and all programs on the OSD DT&E oversight list as well as monitor and review DT&E of MDAPs.

Third, AFOTEC practices the DoD level policy of Integrated DT/OT documented in DoDI 5000.02 in an effort called "Early Influence" (AFOTEC 2010). In order to enhance the Air Force mission, the AFOTEC Commander established a priority to "achieve early and continuous influence for all ACAT I, ACAT II, and DOT&E oversight programs". One of the takeaways for this AFOTEC policy is the early influence and documentation of valid requirements in order to help avoid costly changes later in a system or SoS.

The strategy that AFOTEC uses in executing "Early Influence" can be explained via diagrams in Figure 22, which shows the classic systems engineering Vee applied to system development. Maddocks explained that "Early Influence" starts with a set of operational (i.e. functional) requirements that will provide a capability to the field (AFOTEC 2010). Operational test is intended to evaluate capability, not hardware. This particular Vee diagram (with the horizontal arrows) shows the interaction between the left side (system decomposition and development) and the right side (system integration and test). In practical terms, this implies that as one develops a particular set of requirements (e.g. operational requirements) one should also develop the corresponding test methodology in parallel. This further implies the necessity for operational tester involvement in the development process. The result of this involvement is not only a relevant set of testable requirements, but also a draft test plan. "Early Influence" focuses on the traceability of operational requirements into the system requirements in order to ensure proper scope and tracking of the requirements throughout the designing, building, integration and testing process.

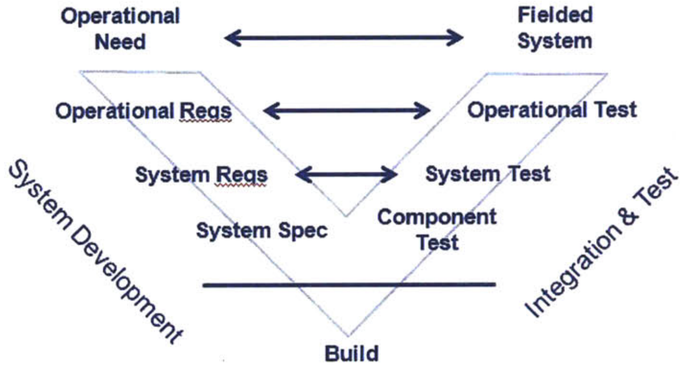


Figure 22 – Strategy for Early Influence (Maddocks 2010)

4.4 – The Process View Explained

The process view examines the "core leadership, lifecycle and enabling processes by which the enterprise creates value for its stakeholders" (Rhodes, Ross and Nightingale 2009). This analysis will focus primarily on the Engineering and Manufacturing Development (EMD) Phase of the DoD acquisition process which occurs between MS B and MS C (see Figure 6). This section of the acquisition process was chosen because this is the time when a system becomes an official DoD acquisition program, which involves more oversight and involvement from the DoD. Also, the generic system that is being discussed is going to be considered a constituent system within the generic systems of systems represented in Figure 1.

The process depicted in Figure 23 is a zoomed in view of the programmatic and test related activities that occur during the EMD Phase of the acquisition process for a constituent system in the SoS (Figure 1). The process mapping in Figure 23 was developed using (USAFOTEC 2010), (Sargeant & Beer 2008), (USAF 2009a) and (DoD 2009). Elements of each source were combined in order to build the process map shown.

There are four main areas identified in Figure 23. The first in the top row is the "Acquisition Processes". These are the events that take place and have a direct impact on the acquisition decisions of the constituent system within the SoS (Figure 1). Another point to make is that this is one of the primary interfaces between the external and internal stakeholders of the constituent system as depicted in the stakeholder waterdrop model in Figure 11. These interfaces are the conduits for information flow from the internal stakeholders to the external stakeholders, which influences the acquisition decisions of the constituent systems. The second row represents the "Developmental Test" (DT) activities that place during the EMD Phase. The third row focuses on the "Integrated Developmental Test and Operational Test" (IDT/OT) activities that occur. Lastly, the fourth row represents the "Operational Test" (OT) EMD related processes. More detail for each track provided below.

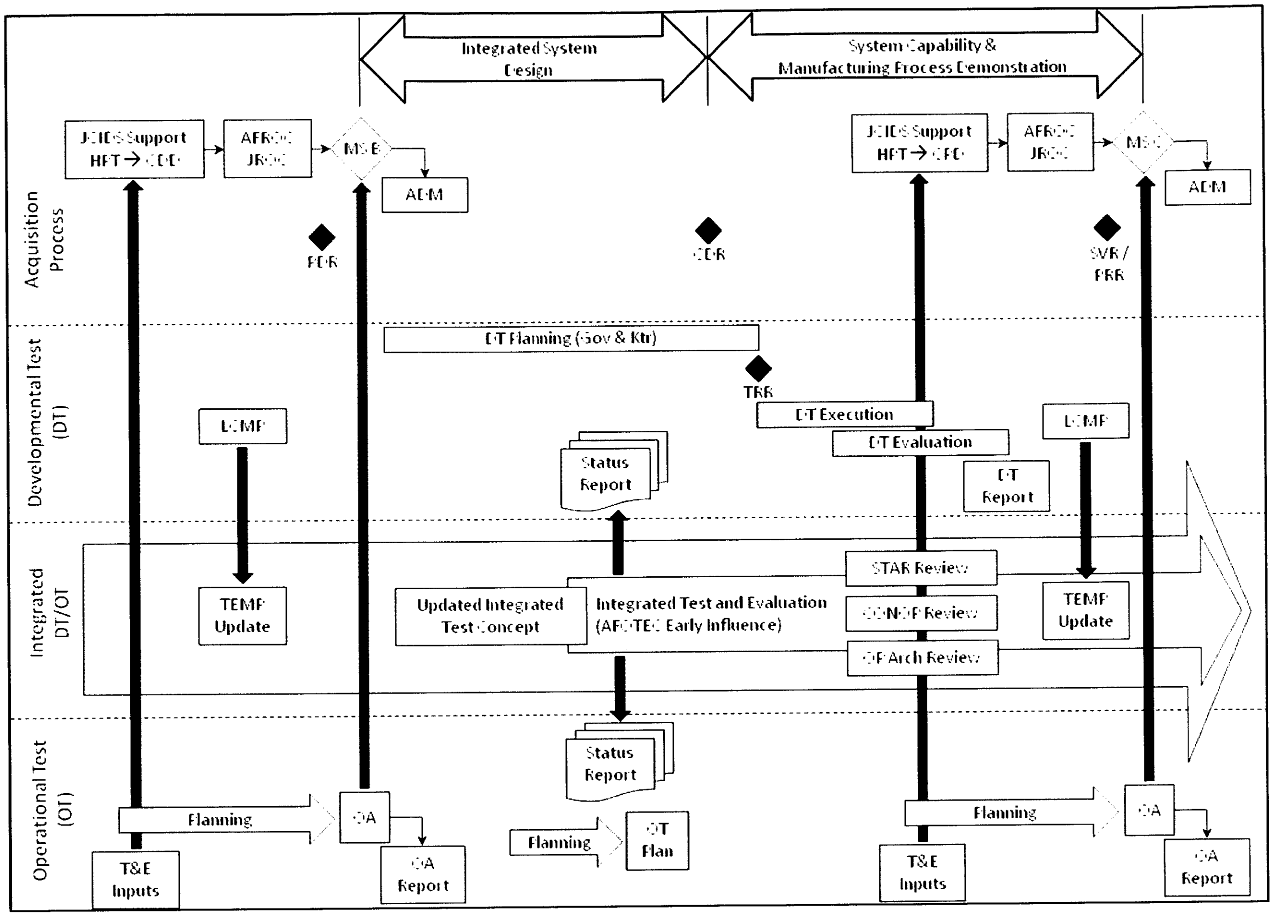


Figure 23 – System Integrated DT / OT Process for MS B to MS C

Acronym Key for Figure 23

- ADM – Acquisition Decision Memorandum
- AFROC – Air Force Requirements Oversight Council
- CDD – Capabilities Development Document
- CDR – Critical Design Review
- CONOP – Concept of Operations
- DT – Developmental Test
- HPT – High Performance Team
- JCIDS – Joint Capabilities Integration and Development System
- JROC – Joint Requirements Oversight Council
- LCMP – Life Cycle Management Plan
- MS B or MS C– Milestone decision points
- OT – Operational Test

- PDR – Preliminary Design Review
- PRR – Production Readiness Review
- STAR – System Threat Analysis Report
- SVR – System Verification Review
- T&E – Test and Evaluation
- TEMP –Test and Evaluation Master Plan

The "Acquisition Process" track starts with a JCIDS update. Here the High Performance Team (HPT), with test representative participation (as indicated by the black arrow), reviews the overall capabilities requirements of the constituent system and how it will interface into the SoS. The HPT provides input into the CDD, which then gets reviewed by either the Air Force Requirements Oversight Council (AFROC) and/or the Joint Requirements Council (JROC) for overall approval and release. A Preliminary Design Review (PDR) occurs and is defined as a "technical assessment establishing the physically allocated baseline to ensure that the [constituent] system under review has a reasonable expectation of being judged operationally effective and suitable" (DAG 2010). The Milestone B decision point then takes place, which officially establishes an acquisition program for the constituent system and is documented by an Acquisition Decision Memorandum (ADM). Here the constituent system is in the first subphase of EMD which is entitled Integrated System Design (ISD) and continues up to the Critical Design Review (CDR). The CDR is a "multi-disciplined technical review establishing the initial product baseline to ensure that the [constituent] system under review has a reasonable expectation of satisfying the requirements of the CDD within the currently allocated budget and schedule" (DAG 2010). Once the CDR is complete, then the component system enters in the EMD subphase of System Capability and Manufacturing Process Demonstration (SCMPD). Toward the end of SCMPD and in preparation for the MS C decision, another HPT meets in order to prepare the Capabilities Production Document (CPD). Also, the System Verification Review (SVR) and Production Readiness Review (PRR) will occur prior to MS C. The SVR is a "multi-disciplined product and process assessment to ensure the [constituent] system under review can proceed into Low-Rate Initial Production and full-rate production within cost (program budget), schedule (program schedule), risk, and other [constituent] system constraints" (DAG 2010). The PRR "examines a program to determine if the design is ready for production and if the prime contractor and major subcontractors have accomplished adequate production planning without incurring unacceptable risks that will breach thresholds of schedule, performance, cost, or other established criteria" (DAG 2010). Once the SVR and PRR are accomplished, then MS C takes place in order for the constituent system to receive approval to enter Low Rate Initial Production (LRIP), which is documented in an ADM.

The "Developmental Test" track in Figure 23 starts with an update to the Life Cycle Management Plan (LCMP) prior to the PDR and also provides input into to the Test and Evaluation Master Plan (TEMP). The LCMP documents "how the program is fielding integrated logistic elements to meet readiness targets, sustain [constituent] system performance capability threshold criteria, mitigating operating and support (O&S) costs, reducing the logistics footprint, and complying with environmental and other logistics related regulations" (DAG 2010). After PDR, both the Government and Contractor start DT Planning, which is the generation of the constituent system test plan in order to verify the constituent system will meet the requirements that have been specified. DT Planning is reviewed at the CDR, which is the lead in activity prior to the Test Readiness Review (TRR). The TRR "assesses test objectives; test methods and procedures; scope of tests and safety; and confirms that required test resources have been properly identified and coordinated to support planned tests; also the TRR verifies the traceability of planned tests to program requirements and user needs" (DAG 2010). Once the TRR is completed, the constituent system enters DT execution, where test missions are conducted per the approved test plan. In conjunction with DT execution, DT evaluation occurs in order to determine the tests that have been conducted meet the objectives established in the test plan. DT execution data can be used in order to support the next JCIDS update and development of the CPD. Also, a DT report is produced by the DT testers and they participate in the SVR and PRR along with providing an update to the LCMP and TEMP.

The "Integrated DT/OT" track in Figure 23 further refines their planning documents, wrapping up the preliminary design phase with a Test and Evaluation Master Plan update and an initial OT&E plan that fleshes out the details of how OT objectives will be addressed by traditional dedicated DT testing activities, such as laboratory and chamber testing. During EMD, developers conduct technical demonstrations to evaluate increments or components of the proposed system. The Integrated DT/OT team is involved to provide status reports on the potential operational effectiveness; suitability; the degree to which they will meet the operational mission need; and any other noted operational issues. In addition, these status reports begin to form an assessment of the systems of systems interfaces required for the constituent system to operate successfully within its operational architecture. In conjunction with the PDR, the Operational Test Authority (OTA) conducts an Operational Assessment (OA) to aggregate the information gathered through the CDR stage to inform the MS C decision on the potential operational effectiveness, suitability, and degree to which they will meet the operational mission need. Additionally, if it is decided during this timeframe to allow the contractor to procure long lead items, part of the OA evaluates the operational aspects of those constituent system components.

The "Operational Test" track in Figure 23 starts with T&E inputs being provided into the JCIDS process. This calls for providing a test representative to be a member of the High Performance Team (HPT) in the support of updating or developing the constituent system CDD. The OT process continues with the planning for an OA which is an interim evaluation of the system by the operational test authority in order to gain an operators perspective into the development of the system prior to the MS B decision. Once the pre MS B OA is completed, then an OA report is written in order to capture the results of the OA. Once MS B has been conducted, the operational testers then continue T&E and further develop an OT Plan for future operational testing. More planning is conducted in order to develop an OT plan prior to CDR. Also, via IDT/OT, the OT community can utilize "Early Influence" in order to develop DT test points that are representative of the operational environment as well as determining which data collected during DT can be used to satisfy operational test requirements. Also, the OT community provides representatives in order to be subject matter experts in the development of the CPD. Lastly, the OT track finishes up with the planning and execution of another OA in support of the MS C LRIP decision.

4.5 – Knowledge and Information Views

As defined in the Chapter 2, the knowledge view examines "the implicit and tacit knowledge, capabilities, and intellectual property resident in the enterprise" and the information view looks at the "information needs of the enterprise, including flows of information as well as the systems and technologies needed to ensure information availability" (Rhodes, Ross and Nightingale 2009). The two views are combined due to their close relation as they pertain to the T&E enterprise.

Knowledge in the T&E enterprise is a very important factor, especially as it will apply to SoS T&E and autonomous systems. Enterprise expertise in these areas will be needed in order or the enterprise to be successful. This knowledge will not just be needed by the Government members of the enterprise, but it will also be needed by all representative stakeholders.

Information is relevant and applicable to all other views in this enterprise. The amount of information that is required to be tracked, transmitted and communicated is voluminous. This is especially true when it comes to systems of systems testing because of all the individual requirements constituent system requirements that have to be developed and tested.

4.6 – Chapter Summary

After conducting this Enterprise Architecture analysis of the T&E enterprise, additional information can be added to the following research question,

- What are primary challenges to UASoS test and evaluation?

The organizational view shows the large geographical separation between the stakeholders. For example, the system program office for a constituent system can be located at Wright Patterson AFB, OH; the contractor that responsible for the system could be located in Rancho Bernardo, CA; and, the test facility can be located at Edwards AFB, CA. The process view shows the conduits between the external and internal stakeholders which can influence the acquisition decisions of the constituent systems. One example is the JCIDS updates that develop the CDD and the CPD prior to MS B and MS C; another example is the identification of the SoS interfaces for the constituent systems. Lastly, the knowledge and information views help to depict the shear amount of information that will be involved during testing of SoS as well as the expert knowledge that will be needed in order to be successful.

Also, information addressing the strategic perspective of the following research question is provided.

- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

There are two aspects that are relevant in addressing this question: the amount of test planning and communication between DT and OT. In regards to test planning, it is important to recognize the amount of test planning that takes place in both the DT and OT during the EMD Phase of the acquisition process. This communication is key for effective test planning of SoS missions because it will enable the implementation of IDT/OT as well as the continuance of AFOTEC's "Early Influence" policy. It is imperative to have effective and continuous communication amongst the members of the Test Integrated Product Team for the constituent system as well as communication between the other systems within the SoS. This is one of the key areas where a DSS can be utilized by the internal stakeholders of the T&E enterprise. Also, this process view shows the value added in conducting Integrated DT/OT because it shows the interaction between the DT and OT communities, which offers a forum for information exchange. This information exchange takes place amongst the members of the Test Integrated Product Team (TIPT) for the constituent system that is being tested as well as the communication with other SoS constituent system TIPTs. The membership of the TIPT has stakeholder representatives that are responsible for developing all relative test aspects of the system undergoing test. Another strategic benefit of utilizing a DSS will increase the amount of communication amongst geographically separated TIPT members as pointed out by the Organization View. Utilization of a DSS tool by the stakeholders will allow important test related information of the constituent system that is undergoing testing to be communicated amongst the stakeholders.

These conclusions also apply to unmanned autonomous systems of systems as well because the same acquisition process will be applied to the constituent system if it manned or unmanned. This is especially true with the future testing within a UASoS framework, which will include high levels of emergent behavior as well as constituent system interfaces and limited resources. Major General Sargeant said it best by saying the "integration of developmental testing and operational testing improves efficiency and, in many cases, allows us to reduce the cost of dedicated OT&E" (Sargeant 2009).

Chapter 5 – Employing a DSS to enable T&E Enterprise UASoS Planning

5.0 – Opening Remarks

This chapter takes into account the tactical analysis of this thesis as mentioned in Chapter 1 and answers the following research question:

- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

In order to address this question an overview of DSS design principles will be presented in order to investigate DSS frameworks, process flow, design characteristics and basic DSS classifications. Next, the results of a DSS "State-of-the-Practice" utilization survey will be presented and a discussion of important DSS Capabilities for UASoS Test Planning will take place in order to provide a linkage and value stream between the strategic analysis and tactical employment. Lastly, this chapter will cover measures of DSS effectiveness by utilizing experiments, quasi-experiments and case studies, which will include an example *PATFrame* use case on value based testing.

5.1 – DSS Frameworks

Gorry and Scott-Morton, in the 1970s, defined a decision support system (DSS) as an interactive computerized system that gathers and presents data from a wide range of sources that help people make decisions (1971). They also created an early decision support framework, Table 14, claiming that decisions are made along two dimensions. The first is "Type of Decision", which is categorized by degree of structure, and the second is "Type of Control", which is categorized by level of control within the organization. The numerical entries in Table 14 are intended to provide a scale in which simple applications are at the low end of the scale and complex tools are at the high end of the scale.

This decision support framework is applicable to the DoD T&E enterprise, especially in the context of future UASoS test planning. It can be argued that current T&E planning capabilities fall into Decision Support Framework categories 1, 2, 4 and 5, which means the test environment is controlled at lower levels (operational & managerial) and is structured & semistructured. The rationale supporting this is that current DoD testing is more or less focused on single-systems that are not autonomous. However, testing of UASoS in the future will require more control at the strategic level to manage the effects of emergent behaviors that manifest between the constituent systems of an SoS and will have to handle more unstructured decisions that are caused by higher levels of autonomy. These are characteristics that drive the need for planning tools that can take into account the complicated test environment that UASoS will present, which correspond to Decision Support Framework categories of 6, 8 and 9 in Table 14.

Table 14 – Decision Support Frameworks (Gorry and Scott-Morton 1971)

	Type of Control		
Type of Decision	Operational Control	Managerial Control	Strategic Control
Structured	1	2	3
Semistructured	4	5	6
Unstructured	7	8	9

5.2 – DSS Process Flow

It is helpful to follow a systematic decision-making process. According to Simon, this involves four major phases: intelligence, design, choice and implementation (1977). A conceptual picture of this decision-making process is shown in Figure 24 (Aronson et al. 2007). There is a continuous flow of activity from intelligence to design to choice, but at any phase, there may be a return to a previous phase. This is an iterative process, because the first time through, the solution can most likely be improved. Therefore, feedback loops are placed into the process from problem discovery, which occurs during the intelligence phase, to solution. These feedback loops are followed as a result of decisions being made at each phase to proceed to the next phase or to return to a previous phase.

The decision-making process starts in the intelligence phase, which is where the decision maker examines reality in order to identify and define the problem. In the design phase, a model is built that represents the system. The choice phase includes selection of a proposed solution to the model. Then, the proposed solution is implemented. Success leads to a possible completion of the task at hand based on how close the model is able to behave like reality or could call for an iteration of the process model for better results. New knowledge leads back to an earlier part of the process (intelligence, design or choice).

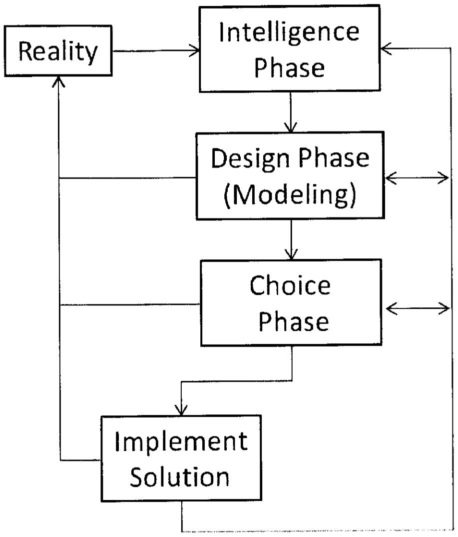


Figure 24 – Decision Process Flow Chart (Aronson et al. 2007)

One can better understand the way test and evaluation is conducted at the tactical level by looking at it through Simon's decision process. T&E starts with Test Planning, which can be thought of as the Intelligence Phase, and this is where the test objectives of the system under test are developed. Test Planning is also where the basic scientific theory is applied to hypothesize the expected results of a test mission. Once Test Planning is complete, then T&E enters the Test Modeling stage. This stage is analogous to a combination of the Design and Choice Phases from Simon's model due to the strong linkage between the test point design and methods selected for testing by the UASoS stakeholders. Here the test sequences are planned, specifically identifying the resources required as well as the sequence of testing events following a build-up approach in task complexity allowing the completion of test objectives within the desired confidence levels. Test Execution is a parallel to the Implementation Phase, and is the stage where test missions are performed as well as data are captured. The last phase is Test Evaluation, which equates to the reality check in Simon's model. This is where the data from testing are examined and compared to the expected predictions from the Test Modeling Phase in order to determine overall results of the test mission. If the desired outcome is achieved, then testing is completed. However, if the expected outcomes are not met then the appropriate portion of the testing cycle will have to be reaccomplished. This is the purpose of the feedback loops in Figure 3 that allow the tester to enter anywhere in the process in order to implement the necessary corrections.

This test and evaluation process also applies to UASoS, but it will need to account for the seven T&E implications of an Acknowledged SoS that was discussed in Table 6 (Chapter 2). This will require strong and continued communication amongst the UASoS stakeholders as well as clearly identified system boundaries to potentially overcome any obstacles that would emerge in the utilization of this framework.

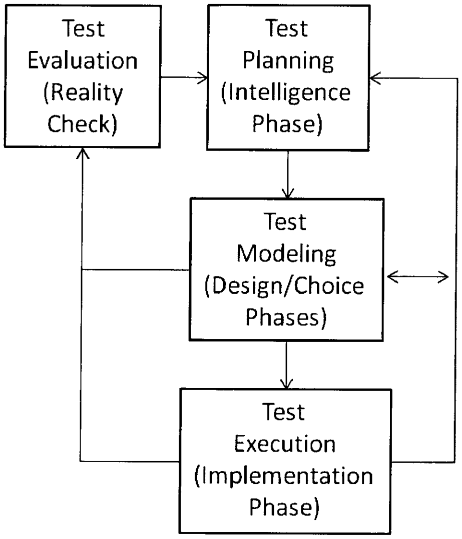


Figure 25 – Test and Evaluation Decision Process Flow Chart

5.3 – DSS Design Considerations

Knowledgeable DSS design characteristics are heuristics that can be used in the development of *PATFrame* to enhance the robustness and versatility that will be required in a UASoS test environment. Robustness is defined as the ability of a system to maintain its level and set of specification parameters in the context of changing system external and internal forces (Rhodes & Ross 2008). Versatility is defined as the ability of a system to satisfy diverse needs for the system without having to change form (Rhodes & Ross 2008).

Efraim and others specify fourteen key characteristics and capabilities of decision support systems (Aronson et al. 2007). The following six characteristics have been chosen to be applicable to *PATFrame* and the Test and Evaluation enterprise's ability to test UASoS because they are the most relevant to the domain under discussion.

- **DSS should provide support for decision makers, mainly in semistructured and unstructured situations by bringing together human judgment and computerized information.** Such problems cannot be solved (or cannot be solved conveniently) by other computerized systems or through the use of standardized quantitative methods or tools. Generally, these problems gain structure as the DSS is developed. This is true with UASoS because of the possibility of unknown emergent behaviors that could exist. The DSS should have the ability to identify when this type of behavior might arise during a mission and possess the ability to display the identified behaviors in a structured manner that enhances human judgment. Also, the selection of tests is not trivial. The DSS needs to provide a means of capturing an unstructured set of multiple criteria in order to allow the decision maker to effectively balance the criteria when making decisions. This allows the tester (i.e., human decision maker) to bring to bear human judgment more effectively and efficiently.

- **DSS should support individuals and groups.** Less-structured problems often require the involvement of individuals from different stakeholders. DSS support virtual teams through collaborative Web tools. DSS have been developed to support individual and group work, as well as support individual decision making and groups of decision makers working somewhat independently. This applies to the arena of future unmanned autonomous systems of systems because it is expected that SoS stakeholders will be geographically separated. Each stakeholder's inputs for testing will need to be considered by *PATFrame* in order for the mission to be adequately planned. Among the stakeholders are developmental and operational testers; program managers; and engineers.

- **DSS should support interdependent or sequential decisions.** The decisions may be made once, several times, or repeatedly. This will hold true for the UASoS T&E simply because of the complex nature of UASoS T&E. There will be the interactions of the autonomous systems under test as well as the internal interactions of the individual system components within the SoS.

- **DSS should provide support in all phases of the decision-making process: intelligence, design, choice and implementation.** In UASoS T&E, this will hold true because the existence of unexpected emergent behavior and limitations on resources (cost, schedule and range availability) necessitate early and iterative strategic decision-making interventions to effectively manage the emergent properties and resource utilization.

- **The decision maker should be reactive, able to confront changing conditions quickly, and be able to adapt the DSS to meet these changes.** DSS should flexible, so users can add, delete, combine, change or rearrange basic elements. They should also be flexible in that they can be readily modified to solve other, similar problems. In UASoS T&E, the notion of emergent behavior is one that can lead to more adaptive test (re)planning.

- **The decision maker should have complete control over all steps of the decision-making process in solving a problem.** A DSS specifically aims to support and not to replace the decision maker. This characteristic of a DSS is important to point out because it is possible for people to think that a DSS is being developed to replace the tester. *PATFrame* is being developed to aid the tester in their ability to plan effective UASoS test missions in the future in order to deliver value to all stakeholders in the T&E enterprise.

Based on DSS design considerations above, it is thought that a DSS with these particular properties that allows a more rigorous test planning capability can assist in overcoming four of the seven SoS challenges identified by Dahman et al. in Table 6. The information shown in Table 15 provides areas of suspected improvement.

Table 15 – Overcoming Acknowledged SoS T&E Challenges

Challenge Number from Table 6	*Methodology in Meeting Stated Challenge identified by Dahman et al. (2010)*
4. Constituent system performance at the SoS level	A DSS can provide assistance in the aggregation of individual system and SoS performance to assist in the preparation of acquisition decisions by providing a consolidated set of data in showing the overall performance of the SoS.
5. Misaligned constituent system schedules	A DSS can provide assistance in aligning the asynchronous schedules that are undergoing testing within the SoS by serving as an SoS integrated master schedule.
6. Number of test points to determine emergent behaviors	A DSS Planning tool can help identify potential emergent behaviors as well as identify test sequences in order to mitigate any perceived risk in the SoS.
7. Increased subjectivity and system alignment	A DSS can aid in overcoming the subjectivity in assessing SoS behavior by providing guidance on how the SoS will behave in the test environment.

5.4 – DSS "State-of-the-Practice"

As with many organizations, the DoD uses decision support systems in order to aid in the decision making process for complex issues. This section focuses on the "State-of-the-Practice" of DSS, and it will cover the following topics: basic DSS classifications that currently exist; review example DSS being utilized by the DoD and industry; and identify which DSS classifications are applicable to *PATFrame*.

5.4.1 – Basic DSS Classifications

The Association for Information Systems (AIS) Special Interest Group on Decision Support Systems (SIGDSS) has produced the following DSS classification schemes (SIGDSS 2010). These classifications are important to describe because *PATFrame* may have some similar characteristics to these types of DSS.

- *Communications-driven and Group DSS (GSS)* – These type of DSS are focused on supporting groups by using computer, collaboration and communication technologies for tasks that may or may not include decision making.

- *Data-driven DSS* – This type of DSS primarily relies on input data and data-processing capability, along with the presentation of this information to a decision maker.

- *Document-driven DSS* – This type of DSS relies on knowledge coding, analysis, search and retrieval for decision support.

- *Knowledge-driven DSS, Data Mining and Management Expert Systems (ES) Applications* – These DSS involve the application of knowledge-generation and knowledge-capture technologies to address specific decision support needs.

- *Model-driven DSS* – The major emphasis of this DSS type is they are primarily developed around one or more (large scale/complex) optimization or simulation models and typically include significant activities in model formulation, model maintenance, and model management in distributed computing environments as well as what-if analyses.

- *Compound DSS* – This type of DSS includes two or more of the aforementioned major DSS categories.

5.4.2 – Examples of DSS Utilization

There are several key DSS applications used by the DoD and industry in order to complete tasks such as task planning, requirements tracing, mission simulation, data referencing, etc. Based on interviews of subject matter experts from various agencies of the Department of Defense, the services, and industry, summary descriptions were developed for the following tools: AWARENess, EBODSS, Oasis, StarShip and Tester. This is a representative snapshot of some of the current DSS tools that are being used in the system of systems arena and is not an all-inclusive listing of utilized DSS.

- *AWARENess* – AWARE Software, Inc based in Austin, TX, developed a decision support system called the AWARENess Suite. It is a SoS tool that uses connected intelligence to deliver on-demand decision support, delivering answers to questions asked by key project stakeholders (AWARE 2010). Connected intelligence refers to the ability to establish communication links between typically stove-piped information. Also, the AWARENess Suite is a web-based computational model that brings distributed business and technology teams together by allowing all information to be in one place and accessible; enable customizable queries by providing dash boards with drill-down capabilities. Lastly, the AWARENess Suite brings together the data, intelligence and decisions from all stakeholders and is applicable to all areas of the design life cycle. The result is that every stakeholder contributes to and reads from a single source. All stakeholders can see inputs from others, current status, planned direction and measured outcomes in an interface customized to their roles and responsibilities.

- *EBODSS (Effects Based Operations Decision Support Services)*: This is a SoS application that supports the Army produced by EMSolutions based in Crystal City, VA. It is a rapid insertion technology tool that fills an emerging warfighting capability gap, which means that the EBODSS was developed based on an urgent warfighter need. EBODSS provides a planning tool to integrate and employ unmanned capabilities that are both existing and emerging for intelligence, surveillance and reconnaissance (ISR) to satisfy information requirements for warfighters (EMSolutions 2010). This tool enables users to effectively plan missions using multiple UAS and UGV systems by providing probabilistic confidence levels of mission accomplishment based on the asset placement. Also, it integrates mission guidance into unmanned aerospace system (UAS) and unmanned ground vehicle (UGV) planning. It analyzes placement of ground motion sensors to meet mission-critical objectives. It allows mission planners to visualize the ISR plan execution within a 2D/3D geospatial environment as well as rapidly integrating a newly-deployed unmanned system.

- *OASIS (OTC Advanced Simulation and Instrumentation Systems)* – The OASIS Enterprise Information System (EIS) is the Army's program of record for its Operational Test Command that acquires expertise and tools to develop, enhance, integrate and operate OTC's test technology enterprise (USAOTC 2010). OASIS was driven by changes in the enterprise such as T&E methodology; technical standards; the system under test; and test control systems/networks. A DSS function of OASIS supports artifacts for planning, control, and management of tests that are rapidly created, reliable and repeatable. Of all of integrated information systems that form the OASIS federation, StarShip is one tool suite that particularly supports systems-of-systems test and evaluation.

- *StarShip* – This is an information suite that is part of the OASIS EIS and forms the function of a DSS that operates within a SoS environment. This tool is a test-control application that provides a test director with the capability to validate the test environment; initialize the test applications; monitor and control test applications and relevant reported properties; gather test results for post analysis activities; and shut down applications as required (USATEC 2009). StarGen, a component of the StartShip suite, provides the test director with a means of planning the test timeline, creating threads to execute various initialization processes or exercise processes, and scheduling these processes for automatic execution. In so doing, the test director is able to script the known required processes to run at specific points in time across the exercise.

- _Tester_ – Recent DoD policy changes have shifted the Test and Evaluation focus from the individual system level up to mission impacts and the value added to current capabilities (Pilar 2010). This led to the development of mission based test and evaluation (MBT&E), which is a methodology that seeks to assess the "strengths and weaknesses" of a system and its components and "the effect on operational capabilities" (Apicella et al. 2009). In order to implement this transition, a web-based application called TESTER (Test and Evaluation Support Tool and Example Repository) has been developed (Pilar 2010). TESTER has several key functions that will (1) provide an online electronic system for evaluators and system stakeholders to work collaboratively on system evaluations; (2) guide users through the MBT&E steps using interactive interfaces (such as drop-down menus) to facilitate an easier-to-use process; (3) develop standardized formats for evaluation products while still allowing content flexibility to meet varying system evaluation needs; (4) link Cross Command Collaboration Effort (3CE) products into system evaluations; (5) ensure standardized system names and schedules by direct connections with the ATEC decision support system; and (6) facilitate storage of documents on a digital library enabling a common document repository.

5.4.3 – Important DSS Capabilities for *PATFrame*

Each one of the identified DSS has attributes that can benefit *PATFrame*. These are key attributes that tie into the testing framework that was defined earlier in this chapter. In pulling this information together, *PATFrame* would benefit by supporting the following functionalities:

- Support key stakeholder involvement such as AWARENess
- Simulate planned mission activities similar to that of EBODSS
- Allow for rapid creation and test planning, control and management similar to that of OASIS-EIS
- Support tester design of test timelines in a similar manner of StarShip
- Provide a knowledge base of accessible test documentation such as that supported by TESTER

5.5 – Experiments, Quasi-experiments and Case Studies

Developing metrics for the effectiveness of test planning for UASoS is important for maturing this area of research. Measuring the effectiveness of a DSS is important because it baselines the performance; determines the applicability of its intended use; and delivers the intended value to all stakeholders. The authors' research has found one possible way of completing these tasks as they pertain to *PATFrame*. This method utilizes experiments, quasi-experiments, and case studies in order to verify and validate the performance of a DSS and will be discussed here. Also, its applicability will be discussed in this section.

Adelman suggests three different ways for evaluating decision support systems: experiments, quasi-experiments, and case studies (1991). Adelman pointed out that experiments are most feasible during the early stages of development when evaluating the proof-of-concept of the DSS prototype as well as assessing the performance adequacy of system features such as a knowledge base. Further, quasi-experiments and case studies are more feasible when used in an operational environment.

According to Adelman, the main purpose of the experiments, quasi-experiments, and case studies is to determine the reliability and validity of the DSS (1991). In this instance, reliability means that operations of the evaluation are repeatable and validity implies that the results of the experimentation are trusted and can be accepted.

5.6 – Evaluating a UASoS Test Planning Tool

PATFrame will demonstrate technologies that meet needs identified by the Unmanned Autonomous System Test Steering Group for the planning of future test and evaluation of UASoS. The goal is to increase the technology readiness level of *PATFrame* over a three-year timeline. Therefore, it is logically appropriate to develop experiments for determining *PATFrame*'s basis of reliability and validity. Performance of *PATFrame* will be determined primarily based on experiments via use cases that will demonstrate the tool's test planning functionality.

Overall, these experiments will demonstrate the robustness of *PATFrame*'s system architecture and the tools ability to function as a DSS to test planning of UASoS. Figure 4 shows the overall *PATFrame* workflow that utilizes the top-level architectural elements that constitute the tool (Edwards et al. 2010).

The evaluation of *PATFrame* will be based on a process similar to that developed and described by Adelman. Requirements have been developed in order to benchmark *PATFrame* in four main technical categories.

- Quality of Service
- Undesired Emergent Behavior

- Prioritization of Testing
- Cost Breakdown of Testing

Specific metrics that assess *PATFrame*'s ability to support these technical categories are being developed. Some of these include:

- Time required to model a system in *PATFrame*
- Accuracy of identifying emergent behavior
- Level of automation in predicting emergent behavior
- Accuracy of cost prediction

The use cases and technical categories can be further enhanced by including stakeholders who represent the Air Force, Army and Navy, based on their role as transition partners from test and evaluation community who anticipate using *PATFrame* in the DoD T&E UASoS enterprise.

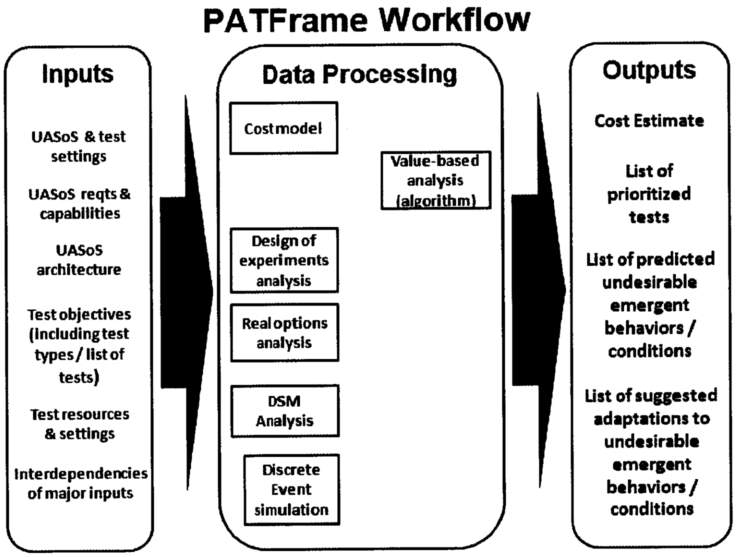


Figure 26 – Overall *PATFrame* Workflow

5.7 – *PATFrame* Use Case Example

5.7.1 – Use Case Description

Use cases as described by Adelman (1991) have been developed for demonstrating and measuring the performance of *PATFrame*. One of these uses cases will be described here in order to provide an example of the value that can be delivered by the utilization of *PATFrame*. Specifically, this use case will demonstrate how *PATFrame* can be used in order to prioritize testing in a systems of systems environment (Kenley & Cowart 2010). The approach used in this use case builds upon a software testing methodology developed by Li (2009) known as value-based testing, and is intended to serve as the principal approach to integrate multiple test prioritization schemes into an overarching prioritization.

The use case scenario (Figure 27 and Figure 28) that is explained is a systems of systems capability upgrade for a set of near full autonomous UAVs that conduct kill-chain functions of CUE, FIND, FIX, TRACK and TARGET and was modified from Dickerson & Morris (2009). The UAVs capture, synthesize, and relay information to geographically separated intelligence cell.

The overall outcome for this use case example is to show how *PATFrame* would be used in order to develop a prioritized set of tests to perform. This would be accomplished by accomplishing the following. First, defining the utility for functions under test will take place. Second, the quality risks and weighting factors will be defined. Third, the cost of testing will be calculated. Lastly, the value-based testing priorities will be determined.

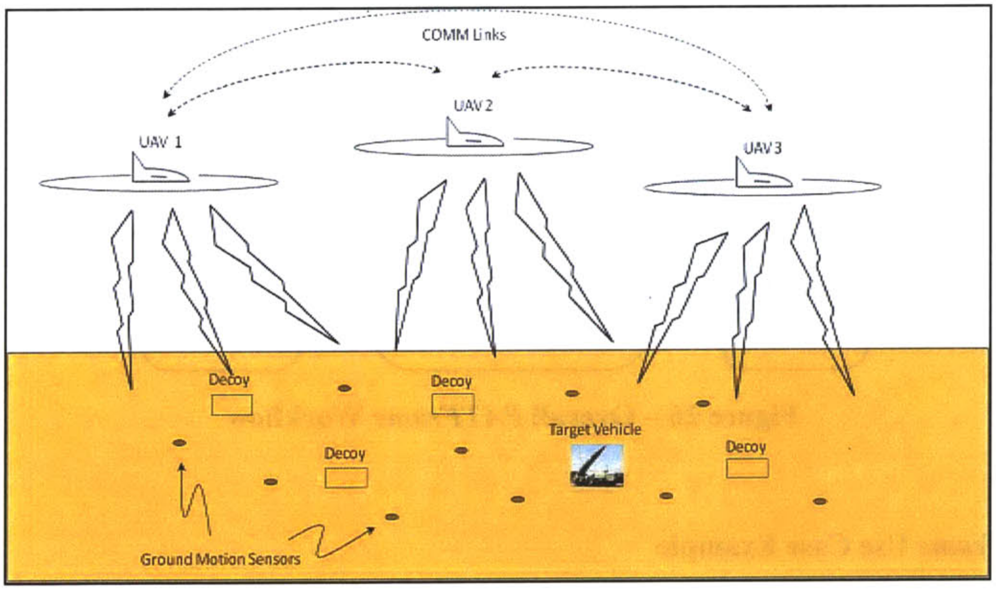


Figure 27 – Use Case Scenario Description (Kenley & Cowart 2010)

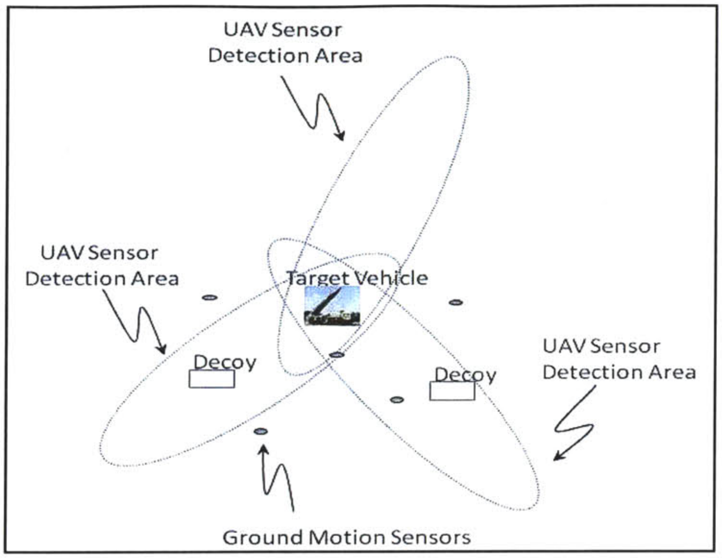


Figure 28 – Overhead Picture of Use Case Scenario Description (Kenley & Cowart 2010)

The actors that will utilize *PATFrame* in order to determine the value-based test plan would be the internal stakeholders identified in Chapter 4: program managers, systems engineers, DT and OT testers. These stakeholders would perform the functions identified in Figure 29.

Figure 29 – Stakeholder Functions for Value-Based Testing (Kenley & Cowart 2010)

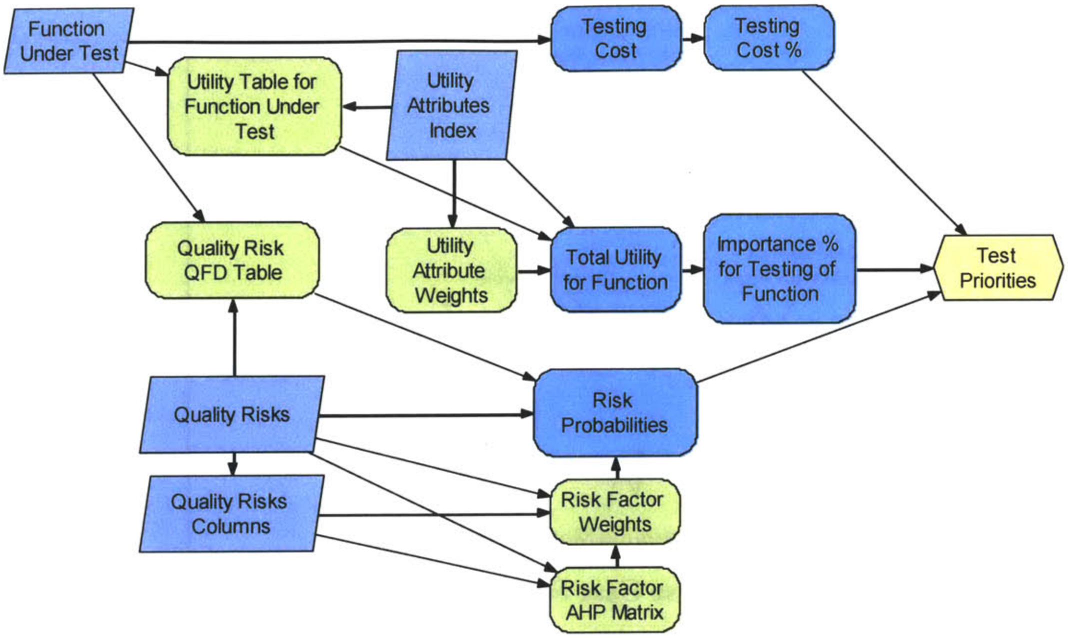


Figure 30 – Value Based Testing Use Case Model Diagram (Kenley & Cowart 2010)

The approach of this use case builds upon a software testing methodology known as value-based testing, and is intended to serve as the principal approach to integrate multiple test prioritization schemes into an overarching prioritization based on the original approach developed by Li (2009).

The executable model is coded in Analytica, which is a general-purpose influence diagram modeling tool used for creating, analyzing, and communicating decision models (Lumina 2010).

The use case prioritizes testing of upgrades of the functionality of near-full autonomous unmanned air vehicles (UAV) that operate in a sytems of systems capability that conduct the kill-chain functions of CUE, FIND, FIX, TRACK and TARGET.

The model (depicted in Figure 30) uses three inputs factors when prioritizing the testing order of the new functions, and they represent the success-critical stakeholders win conditions:

- ***The utility of upgrading the kill-chain functions***: It gives information as to what extent an upgrade to the functionality adds value to the mission of the UAVs within their system of systems context.
- ***The quality risk of each function***: The focus is on identifying programmatic and/or technical risks that are potential value-breakers.

- ***The cost for testing each function***: Test managers are interested in the identification of problems, particularly tests that are inordinately expensive relative to the ultimate value provided by the capability upgrades that are being tested and the programmatic and/or technical risks that are being reduced by testing.

5.7.2 – Examining the Utility of the SoS Upgrades

To determine the utility of the upgrades to each function, Karl Wiegers' approach was applied that considers both the "positive benefit" of the capability upgrade and the "negative impact" of the absence of the upgrade (Wiegers 1999).

The test planners define the functions to be tested, which in this example are CUE, FIND, FIX, TRACK and TARGET, and are captured in the node labeled "Function Under Test". This node can be modified to capture any list of tests that the tester wants to assign utility to. For example, instead of listing functions to be tested, a tester might want to list key interface or systems of systems interaction to be tested where emergent behaviors might be expected.
The program manager is responsible for defining the utility and can rely on expert judgment by representative users. Each function is assessed in terms of the mission benefits it will bring if implemented, as well as the penalty that will be incurred if it is not implemented. The importance of including relative penalty should not be neglected. For example, failing to comply with a government regulation could incur a high penalty even if the customer benefit is low, as would omitting a function that any user would expect, whether or not it was explicitly requested by user.

For each function of the SoS capability upgrade, the "utility" is calculated using a weighted summing formula to produce the "Total Utility for Function" node. The Total Utility is calculated by the following formula.

$$Total\ Utility = W_{Benefit} \times Benefit + W_{Penalty} \times Penalty \qquad \text{(Eq 3)}$$

In this example, benefit is emphasized rather than penalty and weigh the relative benefit as twice as important as the relative penalty, which is entered in the node "Utility Attribute Weights". This can be the case if the new functions are enhancements to existing functions in currently deployed UAVs that already have implemented the main functions required by end users and implementing these functional upgrades will bring more benefit to ends users, while not implementing them will not greatly influence utilization of the UAVs by the end users to achieve their mission objectives.

The estimates of benefits and penalties are relative. A scale of 1 to 9 is used for the utility of each function and is shown in Table 16. In this example, the benefit of CUE, FIND, and TARGET are rated as 1, since they represent minor upgrades to this functionality when compared with FIX and TRACK, which are major upgrades and rated at 9. The penalty for not including the CUE and FIND are rated at 1 because there are other systems in the systems of systems construct that provide CUE and FIND functionality. The penalty for not providing the FIX and TRACK upgrades are at 5 because the UAVs provide the sole means of achieving these functions and the end users are expectantly awaiting these upgrades. These are only rated as a 5, because, hypothetically, much ado has been made about the minor upgrades to the TARGET function by the general staff who have sold the program to Congress and not testing this function would be a grave political mistake. Other instances of assigning a 9 to the penalty occur when a failure to upgrade a function would result operations being shut down for safety reasons. Most recently, for UAVs, this would mean additional functionality requested by the FAA for which provides the end users so very little intrinsic mission value.

Table 16 – Use Case Model Entries for "Utility Attributes Index"

	Utility Attributes	
Function under test	***Benefit***	***Penalty***
CUE	1	1
FIND	1	1
FIX	9	5
TRACK	9	5
TARGET	1	9

The relative contribution of each function is in the node "Importance % for Testing of Function", which is calculated by dividing the Total Utility for Function by the sum of the Total Utility for all functions.

5.7.3 – Examining the Quality Risk of the SoS Upgrades

Most programs have a risk analysis performed prior to beginning system test. The risk analysis can be used to calculate the risk probability for each function being tested. There are three steps in quality risk analysis where the first step is to provide listing all risk factors based on historical projects and experiences. Second, use the AHP (Analytic Hierarchy Process) Method to determine the weight for each risk factor. Third, calculate the risk probability for each function.

Step 1: Define general risk areas for programmatic and/or technical risks: In this example, the following risks identified by Li (2009) were selected: Personnel Proficiency, Size, Complexity, and Design Quality. These should be based on historical considerations of which risk areas are most likely to be the root cause of failures and are entered into the "Quality Risks" node.

Step 2: Determine the weights of each quality risk using the AHP method: AHP is a powerful and flexible multicriteria decision-making method that has been applied to solve unstructured problems in a variety of decision making situations, ranging from the simple personal decisions to the complex capital-intensive decisions. In our example, the calculation of quality risks weights is captured in the node "Risk Factor AHP Matrix". The matrix in this example is extracted from the Li (2009). The number in each cell represents the value pair wise relative importance. A number of 1, 3, 5, 7, or 9 (Table 18) in row ***i*** and column ***j*** stands for that the stakeholder value in row ***i*** is equally, moderately, strongly, very strongly, and extremely strongly more important than the stakeholder value in column ***j***, respectively.

Table 17 – Use Case Risk Factors

Quality Risk Factors	***Programmatic / Technical Risk Considerations***
Personnel Proficiency	Measures the experience base of the personnel who are available to fix any defects found during testing
Size	Measures the amount of components that are incorporated into the function capability
Complexity	Measures the amount of interaction between components that are required to achieve the functional capability. For UASoS, this is a measure of how likely it is that undesirable emergent behaviors will present themselves
Design Quality	Measures the past performance of the organization responsible for designing the function in delivering high quality functionality to be tested. Personnel proficiency measures the specific personnel who are assigned to the project, but design quality measures the quality of organizational processes.

Table 18 – Use Case Weights for Quality Risk Factors

	Quality Risks, j			
Quality Risks, i	***Personnel Proficiency***	***Size***	***Complexity***	***Design Quality***
Personnel Proficiency	1	1	1/4	1/7
Size	1	1	1/3	1/5
Complexity	4	3	1	1/2
Design Quality	7	5	2	1

Step 3: The program manager estimates the relative degree of risk factors associated with each function on a scale from 1 to 9: An estimate of 1 means the risk factor influences the function very little, while 9 indicates serious concerns should be paid about this risk factor. They are captured in the node "Quality Risk QFD Table". The quality risk QFD table is a specific example developed for this use case.

For this example, assume that the personnel who worked on the CUE, FIND, FIX, and TRACK functionality are inexperienced and therefore some errors might exist in this functionality. The size of the functionality (lines of code) is not deemed to be very important. The TRACK functionality has quite complex interactions with the others functions and external interfaces. The FIX and TRACK functionality was developed by "lowest bidders" who have some experience in the field, but the responsible program office is nervous about the contractor's ability to deliver this functionality.

Table 19 – Use Case Relative Degree of Risk Factors

	Quality Risks			
Function Under Test	***Personnel Proficiency***	***Size***	***Complexity***	***Design Quality***
CUE	7	1	1	1
FIND	5	3	3	2
FIX	5	3	5	5
TRACK	5	4	5	5
TARGET	1	4	9	3

The data from the "Quality Risk QFD Table" and the "Risk Factor AHP Matrix" are combined to produce the "Risk Probabilities" for each function. These are equivalent to the probability of failure used in standard risk analysis.

5.7.4 – Testing Cost

The test team estimates the relative cost of testing each function, again on a scale ranging from a low of 1 to a high of 9 (Table 20). The test team estimates the cost ratings can be based on a subjective assessment or by using the *PATFrame* effort estimation, which may take into account model factors such as the development effort of required for the function, the function complexity, and the quality risks (Deonandan et al. 2010). The costs are entered into the node "Testing Cost" and they are converted to percentages relative to the total in the node "Testing Cost %"

Table 20 – Use Case Function Test Cost Importance

Function Under Test	*Testing Cost*
CUE	2
FIND	5
FIX	5
TRACK	9
TARGET	9

5.7.5 – Putting It All Together

The value priority number for testing each function is an expected-benefit-to-cost ratio:

$$Test\ Priorities = Risk\ Probabilities \times \frac{Importance\ \%\ for\ Testing\ of\ Function}{Testing\ Cost\ \%} \qquad \text{(Eq 4)}$$

After a round of testing is completed, the costs and risk can be updated based on test results, and the priorities for the next round can be re-calculated.

The Analytica modeling method also allows for assigning probability distributions to any variable, including anticipated costs and risks after round of testing and the impact on costs and risk of incorporating real options that may be available for each round of testing. This allows for determining the benefit-cost ratio of real options that add certain flexibilities into the test infrastructure and into the design of the system under tests.

5.8 – Chapter Summary

This chapter investigated how a decision support system such as *PATFrame* can be developed in order to facilitate the ability of testers to effectively plan UASoS test missions at the tactical level. In doing so, this chapter was intended to answer the following research question.

- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

This question was answered by examining key aspects of decision support systems that can help a DSS to potentially help in overcoming four of the seven SoS T&E challenges identified by Dahman et al. (2010) which are depicted in Table 15. Also Simon's general decision process (Figure 24) was related to the processes of test and evaluation (Figure 25). In addition, a "State-of-the-Practice" survey was conducted in order to identify key decision support systems that are used within industry and the Department of Defense in order to obtain an understanding of some key capabilities that could possibly benefit *PATFrame*, as shown in Section 6.6: The key capabilities identified in the survey support key stakeholder involvement; allow the simulation of planned mission activities; allow for rapid scenario creation and test planning, control and management; support tester design of test timelines; and provide a knowledge base of accessible test documentation. Lastly, a strategy was proposed for the evaluation of *PATFrame* based on experiments via use cases that will demonstrate the ability of planning UASoS test and evaluation missions in order to provide a basis for serving as a Measure of Performance. An example was used that explained the Value Based Testing use case developed by Kenley and Cowart (2010).

Chapter 6 – Conclusions and Future Research

6.0 – Opening Remarks

This chapter will summarize the overall results of the research questions that were presented in Chapter 1. Also, this chapter provides insight into the overall value that can be gained by the development of *PATFrame* for the purpose of T&E of UASoS.

6.1 – Conclusions

Recall, the research questions addressed in this thesis were strategically and tactically focused as discussed in Chapter 1. The strategically focused research questions with the associated answers are as follows:

- How is test and evaluation from a system perspective different than that of systems of systems?

This question was answered in Chapter 2 via comparison of a system to systems of systems and clarifying the role of test and evaluation in each. It was determined that the role of test and evaluation in a system is executable, but can be encumbered by system complexities such as software functions as shown in Table 3. SoS T&E is more complicated due to a multitude of challenges such as those identified by the DoD SoS Engineering Guidebook in Table 5 and Dahman et al. (2010) in Table 6.

- Who are the primary stakeholders of the test and evaluation enterprise?

This question was addressed in Chapter 3 from an Air Force perspective and listed the primary T&E stakeholders in Table 11. In addition, a stakeholder saliency analysis was accomplished for the identified stakeholders and is shown in Table 12.

- What are primary stakeholder values towards unmanned autonomous systems of systems testing?

This question was answered in Chapter 3 as well and the results were based on stakeholder interviews that were conducted using the questionnaire framework that is shown in Appendix C. The expected value statements of the stakeholders along with the "Relative Value Importance" and "Current Value Delivery" are summarized in Table 13.

- What are primary challenges to UASoS test and evaluation?

Information to answer this question was obtained from the stakeholder interviews that were covered in Chapter 3 as well as the "As-Is" enterprise architecture analysis that was covered in Chapter 4. A summary listing of primary challenges that resulted from the stakeholder interviews is repeated in the following bullet list:

- Ensure smooth transition from DT to OT for constituent members of the SoS
- Have the ability to predict potential emergent behaviors (both good and bad) and be able to test these emergent behaviors within the available resources
- Be able to build the constituent systems to design specifications and understand the required SoS interfaces
- Be able to scope and understand the test risks and develop risk mitigation plans
- Build and establish continued trust amongst the SoS team members
- Ensure stability of SoS requirements in order to not extend required time for testing

The architecture analysis results from Chapter 4 produced the following challenges. The organizational view shows the large geographical separation between the stakeholders. For example, the system program office for a constituent system can be located at Wright Patterson AFB, OH; the contractor that responsible for the system could be located in Rancho Bernardo, CA; and, the test facility can be located at Edwards AFB, CA. The process view shows the conduits between the external and internal stakeholders which can influence the acquisition decisions of the constituent systems. One example is the JCIDS updates that develop the CDD and the CPD prior to MS B and MS C; another example is the identification of the SoS interfaces for the constituent systems. Lastly, the knowledge and information views help to depict the shear amount of information that will be involved during testing of SoS as well as the expert knowledge that will be needed in order to be successful.

The last research question was as follows:

- How can a decision support system be utilized in order to deliver value to the T&E enterprise?

This question was addressed from both a strategic perspective offered in Chapter 4 and addressed at the tactical level in Chapter 5. Based on the "As-Is" Enterprise Architecture analysis in Chapter 4, there are two aspects that are relevant in addressing this question from a strategic perspective: First, it is imperative to have effective and continuous communication amongst the members of the Test Integrated Product Team for the constituent system as well as communication between the other systems within the SoS. Second, utilizing a DSS will increase the amount of communication amongst geographically separated TIPT members as pointed out by the Organization View and the use of a DSS tool by the stakeholders will allow important test related information of the constituent systems to be communicated amongst the stakeholders. And from Chapter 6, this question was answered by examining key aspects of decision support systems that can help a DSS to potentially help in overcoming four of the seven SoS T&E challenges identified by Dahman et al. (2010) which are depicted in Table 15. Also Simon's general decision process (Figure 24) was related to the processes of test and evaluation (Figure 25). In addition, a "State-of-the-Practice" survey was conducted in order to identify example decision support systems that are used within industry and the Department of Defense in order to obtain an understanding of some key capabilities that could possibly benefit *PATFrame*, as shown in Section 5.4.3: The key capabilities identified in the survey support key stakeholder involvement; allow the simulation of planned mission activities; allow for rapid scenario creation and test planning, control and management; support tester design of test timelines; and provide a knowledge base of accessible test documentation. Lastly, a strategy was proposed for the evaluation of *PATFrame* based on experiments via use cases that will demonstrate the ability of planning UASoS test and evaluation missions in order to provide a basis for serving as a Measure of Performance. An example was that explained the Value Based Testing use case developed by Kenley and Cowart (2010).

6.2 – Future Value Considerations for UASoS Test and Evaluation

There are several future value considerations for UASoS capabilities, which can be viewed through two perspectives. The first perspective is via the Enterprise Transformation Principles discussed by Nightingale and Srinivasan (2011) and the second perspective is from the "-ilities" developed by Rhodes and Ross (2008).

Based on the Enterprise Transformation Principles, future value for UASoS T&E via the use of a DSS such as *PATFrame* can be realized by:

- Adopting a holistic approach to enterprise transformation – This calls for the manned system focused T&E enterprise to include the recognize the primary stakeholders and understand their value streams and salience in order to provide the capability needs to the user that are defending the United States of America.

- Secure leadership commitment to drive and institutionalize enterprise behaviors – The changes necessary in order to deliver the value to the UASoS T&E community will have to start at the top of the leadership chain. This will set the initial direction of the changes necessary and will need the continued focus of leadership in order for the continued delivery of value to the user.
- Identify relevant stakeholders and determine their value propositions – An example of the UASoS T&E stakeholders and saliency was conducted in this thesis and shows the relative importance of the stakeholders. In order to continuously deliver the value to the user, one must keep in mind that the stakeholders position in the enterprise is not static. It must continuously be evaluated in order to determine if a stakeholder's position has changed.
- Focus on enterprise effectiveness before efficiency – This principle implies that the UASoS T&E enterprise will need to develop the necessary methodology and processes for effectively testing UASoS before shortcuts can be made. This will be especially true for constituent system interfaces and emergent behaviors.
- Address internal and external enterprise interdependencies – This is something that was identified during the stakeholder interviews in Chapter 4 It is important to understand what is within the enterprise boundaries and outside of those boundaries because it is easier to make changes it is internal. This is also a dynamic property where what is inside the enterprise one day might be outside of the enterprise the next.
- Ensure stability and flow within and across the enterprise – This is important because T&E is about identifying and removing risk. It is imperative to a stable process that allows continuous flow in the enterprise. A DSS tool such as *PATFrame* is a mechanism that would enable the stability and flow necessary to identify potential risks in UASoS T&E.
- Emphasize organizational learning – This principle applies to UASoS T&E because this is a new frontier. In order for the value to be realized, then the personnel of the T&E enterprise will need to be educated in the tools at their disposal in order to properly deliver the capabilities to the warfighter.

Lastly, future value of an UASoS T&E planning tool such as *PATFrame* can be viewed through the "-ilities": *Robustness* will allow the T&E enterprise to capture the iterative nature of asynchronous constituent systems. *Versatility* will allow an understanding of the constituent system designs and interfaces at the SoS level. *Changeability* will allow the capture the changes over time as T&E resource requirements change (i.e., time, money, materials, and level-of-effort). *Flexibility and Adaptability* allow properties of constituent systems to be updated over time reinforcing the concept of integrated DT/OT. Lastly, *Scalability and Modifiability* allow the capture of changes in the testing driven by scaled or modified capability requirements.

6.3 – Next Steps

The following are recommended next steps in order to continue the research related to the test and evaluation of unmanned autonomous systems of systems:

- Share results of this research with DoD T&E leadership in order to obtain strategic enterprise buy-in to the technology that is being developed
- Establish long-term transition partner buy-in in order to progress the development of this approach
- Continue research and pursue the development of the *PATFrame* DSS approach for the planning capability for the UASoS test and evaluation
- Conduct further research into the other areas of the acquisition lifecycle in order to shed light on how UASoS DSS planning capability can be applied

(THIS PAGE INTENTIONALLY LEFT BLANK)

Bibliography

Adelman, L. (1991). Experiments, Quasi-Experiments, and Case Studies: A Review of Empirical Methods for Evaluating Decision Support Systems. *IEEE Transactions on Systems, Man and Cybernetics , 21* (2), 293-301.

Apicella, F., C. Wilcox and K. Wyant. (2009). Army Test and Evaluation Command (ATEC) Initiatives in Response to the Office of the Secretary of Defense Policy Guidelines on Test and Evaluation. *ITEA Journal , 30*, 361-368.

Armed Forces Communications and Electronics Association Website. (n.d.). Retrieved September 11, 2010, from http://www.afceaboston.com

Aronson, J., T.P. Liang, R. Sharda and E. Turban. (2007). *Decision Support and Business Intelligence Systems.* Upper Saddle River, NJ: Prentice Hall.

Association for Information Systems (AIS) Special Interest Group for Decision Support Systems (SIGDSS). (n.d.). Retrieved August 4, 2010, from http://sigs.ais.org/SIGDSS

AWARE Software, Inc. (n.d.). *AWARENess Suite Overview*. Retrieved August 9, 2010, from http://www.awaresoftware.com

Babbie, E. (2004). *The Practice of Social Research* (10th ed.). Belmont, CA: Thomson and Wadsworth.

Bar-Yam, Y. (2004). The Characteristics and Emerging Behaviors of System of Systems. *NECSI: Complex Physical, Biological and Social Systems Project* , 1-16.

Browning, T. (1998). Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development. Cambridge, MA: MIT.

Burgess, C.N. (2010). Value Based Analysis of Acquisition Portfolios. Cambridge, MA: MS Thesis, MIT.

Carlock, P.G. and R.E. Fenton. (2001). Systems (SoS) Enterprise Systems Engineering for Information-intensive Organizations. *Systems Engineeing , 4*, 242.

Carney, D. D. (2005). Topics in Interoperability: Systems-of-Systems Evolution. Pittsburgh, PA: Software Engineering Institute, Carnegie Mellon University.

Carter, G.M., M.P. Murray, R.G. Walker and W.E. Walker. (1992). *Building Organizational Decision Support Systems.* Boston, MA: Academic Press Inc.

Cook, S. (2001). On the Acquisition of Systems of Systems. *11th Annual INCOSE Symposium.* Melbourne, Australia.

Cooper, R. and R. Slagmulder. (1997). *Target Costing and Value Engineering.* Portland, OR: Productivity Press. Montvale, NJ: IMA Foundation for Applied Research.

Coyle, P. (2010). Continuity or Expertise, T&E and Defense Acquisition Reform. *Test Week 2010.* Huntsville, AL.

Crawley, E. (2010, October 8). Identifying Value - Reducing Ambiguity in the System. Cambridge, MA.

Crossley, W. (2004). System of Systems: An Introduction of Purdue University Schools of Engineering's Signature Area. *Engineering Systems Symposium.* Cambridge, MA.

Dahman, J., J. Lane, R. Lowry and G Rebovich. (2010). Systems of Systems Test and Evaluation Challenges. *5th IEEE International Conference on Systems of Systems Engineering.* Loughborough, UK.

Dahmann, J. and K. Baldwin. (2008). Understanding the Current State of US Defense Systems of Systems and the Implications for Systems Engineering. *IEEE Systems Conference.* Montreal, Canada.

Defense Acquisition University (DAU). (n.d.). *Defense Aquisition Guidebook.* Retrieved November 2010, from https://dag.dau.mil

DeLaurentis, D. (2005). Understanding Transportation as a System of Systems Design Problem. *AIAA Aerospace Sciences Meeting.* Reno, NV.

Deonandan, I. ,R. Valerdi, J. Lane and F. Macias. (2010). Cost and Risk Considerations for Testing Unmanned and Autonomous Systems of Systems. *IEEE Systems of Systems Engineering Conference.* Loughborough, England.

Department of Defense. (2010, May 5). *Chapter 4: Systems Engineering.* Retrieved October 2010, from Defense Acquisition Guidebook (DAG) Website: https://dag.dau.mil

Department of Defense. (n.d.). *Director or Operational Test and Evaluation Website*. Retrieved July 2010, from http://www.dote.osd.mil

Department of Defense. (2009, March 1). Joint Capabilities Integration and Development System (JCIDS). *Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 3170.01G* .

Department of Defense. (2004, March 8). Test Resource Management Center Website. *DoDD 5105.71* . Washington, DC.

Department of Defense. (n.d.). *US Air Force Materiel Command Services Website*. Retrieved September 11, 2010, from http://afmcservices.org/index.php?tag=map%20page

Department of Defense. (n.d.). *US Air Force Materiel Command Website*. Retrieved September 11, 2010, from http://www.afmc.af.mil/units/index.asp

Department of Defense. (n.d.). *US Air Force Test and Evaluation Center Website*. Retrieved September 11, 2010, from http://www.afotec.af.mil/main/welcome.asp

DeSanctis, G. and R.B. Gallupe. (1987). A Foundation for the Study of Group Decision Support Systems. *Management Science , 33.*

Dickerson, C. E., and D. N. Marvis. (2009). *Architecture and Principles of System Engineering.* Baco Raton, FL: Auerbach Publications.

Dipetto, C. (2010). WSARA and DT&E within the DoD. *26th NDIA National Test and Evaluation Conference.* San Diego, CA.

Dunaway, D. (2008). Unique Range Challenges of UAV/RPV/UUV Test and Evaluation. *24th Annual NDIA National Test and Evaluation Conference.* Palm Springs, CA: National Defense Industry & Technology.

Edwards, G., S. Ferreira, D. Ligett, N. Medvidovic, and R. Valerdi. (2010). PATFrame Architecture and Workflow. *MIT Unmanned Systems Mini-Conference.* Cambridge, MA.

Eisner H., J. M. (1991). Computer-Aided System of Systems (S2) Engineering. *IEEE International Conference on Systems, Man and Cybernetics.* Charlottesville, VA.

Eisner, H. (1993). RCASSE: Rapid Computer-Aided Systems of Systems Engineeing. *3rd International Symposium of the National Council of Systems Engineering*, *1*, pp. 267-273.

EMSolutions, Inc. (2010). Effects Based Operattions Decision Support Services. Washington, DC.

Feickert, A. and N.J. Lucas. (2009, November 20). Army Future Combat System (FCS) Spin-Outs and Ground Combat Vehilce: Background and Issues for Congress. Congressional Research Service.

Ferreira, S., R. Valerdi, N. Mevidic, J. Hess, I. Deonandan, T. Tenario, F. Macias, and G. Shull. (2010). Unmanned and Autonomous Systems of Systems Test and Evaluation: Challenges and Opportunities. *IEEE Systems Conference 2010.* San Diego, CA.

Frooman, J. (1999). Stakeholder Influence Strategies. *The Academy of Management Review , 24* (5), 191-205.

Giadrosich, D. (1995). *Operations Research Analysis in Test and Evaluation.* American Institute of Aeronautics and Astronautics.

Gorry, G.A and M.S. Scott Morton. (1971). A Framework for Management Information Systems. *Sloan Manaagement Review , 13* (1).

Grossi, I. (2003). Stakeholder Analysis in the Context of the Lean Enterprise. Cambridge, MA: MS Thesis, MIT.

Hawkins, K. (2010, March 26). *Saving Soldier Lives with Unmanned Systems.* Retrieved July 18, 2010, from http://www.army.mil/-news/2010/03/26/36450-saving-soldier-lives-with-unmanned-systems

Hennigan, W. (2010, November 18). *Eyes, Ears of US Military Take Shape in High-Tech Labs.* Retrieved November 18, 2010, from http://www.physorg.com/news/2010-11-eyes-ears-military-high-tech-labs.html

Hess, J. and R. Valerdi. (2010). Test and Evaluation of a SoS Using a Prescriptive and Adaptive Testing Framework. *5th IEEE International Conference on Systems of Systems.* Loughborough, UK.

Holland, J. (1995). *Hidden Order How Adaptation Builds Complexity.* Cambridge, MA: Helix Books.

Huang, H.M., E. Messina and J. Albus. (2007, December). Autonomy Levels for Unmanned Systems (ALFUS) Framework. *Volume II: Framework Models 1.0* . NIST - National Institute of Standards and Technology.

Hughes, D. (2007, February). UAVs Face Hurdles in Gaining Access to Civil Airspace. *Aviation Week* .

International Council on Systems Engineering. (2010). Systems Engineering Handbook A Guide for Lifecycle Processes and Activities. *Version 3.2* . San Diego, CA.

Isaac, S. and W.B. Michael. (1997). *Handbook in Research and Evaluation: For Education and the Behavioral Sciences.* San Diego, CA: Educational and Testing Services.

Joint Interoperability Test Command. (n.d.). Retrieved October 13, 2010, from http://jitc.fhu.disa.mil

Kaufman, J. (1985). Value Engineering for the Practitioner. Raliegh, NC: North Carolina State University.

Keating, C. R.-P. (2003). Systems of Systems Engineering. *EMJ - Engineering Management Journal* , *15*, 36.

Keen, P. (1978). *Decision Support Systems: An Organizational Perspective.* Addison-Wesley.

Kenley, R. and K. Cowart. (2010). Value-Based Testing. *PATFrame - Year 1 Milestone Review* (pp. 86-92). Cambridge, MA: MIT.

Lane, J. and R. Valerdi. (2005). Synthesizing SoS Concepts for Use in Cost Estimation. *IEEE Transactions on Systems, Man, and Cybernetics.*

Lean Aerospace Initiative. (1998). Detailed PD Process Model. Output from LAI Product Development Workshop. Los Angeles, CA.

Li, Q., M. Li, Y. Yang, Q. Wang, T. Tan, B. Boehm and C. Hu. (2009). Bridge the Gap between Software Test Process and Business Value: A Case Study. *International Conference on Software Process: Trustworthy Software Development Processes*, (pp. 212-223).

Lui, S., A. Duffy, R.I. Whitfield and I.M. Boyle. (2008). An Integrated Decision Support Environment for Organizational Decision Making. *International Conference on Collaborative Decision Making.* France.

Lumina. (n.d.). *Lumina Decision Systems.* Retrieved November 4, 2010, from http://www.lumina.com

Luskasik, S. (1998). Systems, Systems of Systems, and the Education of Engineers. *Artifical Intelligence for Engineering Design, Analysis, and Manufacturing , 12*, 55-60.

Maddocks, B. (2010, August 25). Integrated Testing in a Complex Remote Piloted Aircraft Environment: A Systems View. *MIT Unmanned Systems Mini-Conference.* Cambridge, MA.

Maier, M. (1998). Architecting Principles for Systems of Systems. *Systems Engineering, Vol. 1, No. 4* , pp. 267-284.

Manthorpe Jr, W. (1996). The Emerging Joint System of Systems: A System Engineering Challenge and Opportunity for APL. *John Hopkins APL Techincal Digest (Applied Physics Laboratory) , 17*, 305.

McManus, H., M. Richards, A. Ross and D. Hastings. (2007). A Framework for Incorporating "illities" in Tradespace. *American Institute of Aeronautics and Astronautics* . Long Beach, CA.

Miles, L. (1961). *Techniques of Value Analysis and Engineering.* New York, NY: McGraw-Hill Book Company.

Mitchell, R., B. Agle, and D. Wood. (1997). Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who. *The Academy of Management Review , 22* (4), 853-886.

Monarch, I.A. and J. Wessel. (2005). Autonomy and Interoperability in System of Systems Requirements Development. *16th IEEE International Symposium on Software Reliability Engineering.* Chicago, IL.

Mudge, A. (1971). *Value Engineering: A Systematic Approach.* New York, NY: McGraw-Hill Book Company.

Murman, E., T. Allen, K. Bozdogan, J. Cutcher-Greshenfeld, D. Nightingale, E. Rebentisch, T. Shields, F. Stahl, M. Walton, J. Warmkessel, S. Weiss, S. Widnall. (2002). *Lean Enterprise Value.* New York, NY: Palgrave.

Nightingale, D. and D. Rhodes. (2004). Enterprise Systems Architecting: Emerging Art and Science within Engineering Systems. *MIT Engineering Systems Symposium* . MIT.

Nightingale, D. and J. Srinivasan. (2011). *Beyond The Lean Revolution: Achieving Successful and Sustainable Enterprise Transformation.* Publication in Progress.

Nightingale, D. (2010, November 17). Enterprise Architecture. ESD-61J - Integrating the Lean Enterprise Lecture Slides. Cambridge, MA: MIT.

Nightingale, D. (2009). Principles of Enterprise Systems. *Second International Symposium on Engineering Systems.* Cambridge, MA.

Office of the Deputy Under Secretary of Defense for Acquisition and Technology. (2008). Systems Engineering Guide for Systems of Systems, Version 1.0. Washington, DC: ODUSD(A&T)SSE.

Office of the Deputy Under Secretary of Defense for Acquisition, Technology and Logistics. (2009). FY2009-2034, Unmanned Systems Integrated Roadmap. Washington, DC: Department of Defense.

Office of the Deputy Under Secretary of Defense for Acquisitions, Technology and Logisitics. (2008). Operation of the Defense Acquisition System. *DoDI 5000.02* . Department of Defense.

Office of the Secretary of Defense. (2008, April 4). Unmanned and Autonomous Systems Testing (UAST). *Broad Agency Announcment (BAA UAST0020)* .

Office of the Under Secretary of Defense for Acquisition, Technology and Logisitics. (2002, September 10). Configuration Management Guidance. *MIL-HDBK-61B* . Department of Defense.

Office of the Under Secretary of Defense for Acquisition, Technology and Logisitics. (2010, March 29). Defense Science Board Task Force on the Role of Autonomy in Department of Defense Systems. *Memorandum for Chairman of Defense Science Board* .

Office of the Under Secretary of Defense for Acquisition, Technology and Logistics. (2009). Implementation of the Weapon Systems Acquisition Reform Act of 2009. *Directive-Type Memorandum (DTM) 09-027* . Department of Defense.

Office of the Under Secretary of Defense for Acquisition, Technology and Logistics. (2008, May). Report of the Defense Science Board Task Force on developmental T&E. Washington, DC: Department of Defense.

Parks, R.C., R.A. Jung and K.O. Ramotowski. (2004). Attacking Agent-Based Systems. *IEEE 1st Symposium on Multi-Agent Security and Survivability.* Philadelphia, PA.

Pei, R. (2001). Systems of Systems Integration (SoSI) - A Smart Way of Acquiring C4ISRWS Systems. *Summer Computer Simulation Conference.*

Pilar, J. (2010). Test and Evaluation Support Tool and Example Repository (TESTER). *ITEA Journal* , *31*, 109-111.

Purdue. (2005). *System of Systems Research Report.* West Lafayette, IN: Purdue University.

Rhodes, D. A. (2009). Architecting the Systems of Systems Enterprise: Enabling Constructs and Methods from the Field of Engineering Systems. *SysCon2009 - IEEE International Systems Conference.* Vancouver, Canada.

Rhodes, D.H. and A.M. Ross. (2008). Architecting Systems for Value Robustness: Research Motivations and Progress. *2nd Annual IEEE Systems Conference.* Montreal, Canada.

Rouse, W. (2005). Enterprises as Systems: Essential Challenges and Approaches to Transformation. Atlanta, GA: Georgia Institute of Technology.

Sage, A. and C.D. Cuppan. (2001). On the Systems Engineering and Management of Systems of Systems and Federations of Systems. *Information, Knowledge, Systems Management*, *2*, 325-345.

Sage, A. (2003). Conflict and Risk Management in Complex System of Systems Issues. *IEEE International Conference on Systems, Man and Cybernetics.*

Sage, A. (1992). *Systems Engineering.* John Wiley and Sons, Inc.

Sargeant, S. (2010). AFOTEC's Pursuit of Acquisition Excellence. *Test Week 2010.* Huntsville, AL.

Sargeant, S. and S. Beers. (2008). AFOTEC's Space Test Initative: Transforming Operational Testing and Evaluation of Space System Capabilities. *International Test and Evaluation Association (ITEA) Journal*, 351-359.

Sargeant, S. (2009). Improving AFOTEC's Contribution to the Acquisition Process: Moving Integrated Developmental and Operational Test to the Next Level. *ITEA Journal*, *30*, 183-189.

Sauser, B. and J. Boardman. (2006). Systems of Systems - The Meaning of Of. *2006 IEEE/SMC International Conference on System of Systems Engineering.* Los Angeles, CA.

Shenhar, A. (2001). One Size Does Not Fit All Projects: Exploring Classical Contingency Domains. *Management Science*, *47*, 394-414.

Shillito, M.L. and D.J. De Marle. (1992). *Value: Its Measuremen, Design and Management.* New York, NY: John Wiley & Sons.

Simon., H. (1977). *The New Science of Management Decision.* Englewood Cliffs, CA: Prentice Hall.

Slack, R. (1999). *The Lean Value Principle in Military Aerospace Product Development.* Cambridge, MA: MIT.

SoSECE. (2003, September). System of Systems Management - Adapted from Glossary, Defense Acquisition Acronyms and Terms, Eleventh Edition. *System of Systems Engineering Center of Excellence* .

SoSECE. (2005, November 9). What is System of Systems (SoS). *System of Systems Engineering Center of Excellence* .

Stanke, A. (2001). A Framework for Acheiving Lifecycle Value in Product Development. Cambridge, MA: MS Thesis, MIT.

Tien, J.M. (2008). Services: A System's Perspective. *IEEE Systems Journal* , *2* (1), 146-157.

Title 10 US Code, Chapter 4, Section 139. (n.d.). Director of Operational Test and Evaluation.

United States Air Force. (2009). Air Force Instruction 99-103. *Capabilities Based Test and Evaluation* .

United States Air Force. (2010, April). Air Force Operational Test and Evaluation Center (AFOTEC) Strategic Plan. *Air Force Directive 100624-073* .

United States Air Force. (2009, March 20). Capabilities-Based Test and Evaluation. *Air Force Instruction 99-103* .

United States Air Force Operational Test and Evaluation Center. (2010, January 6). *Program Manager's Operational Test Toolkit* .

United States Air Force. (2009, November 19). *RQ-4 Global Hawk.* Retrieved November 18, 2010, from http://www.af.mil/information/factsheets/factsheet.asp?id=13225

United States Army Operational Test Command. (2010, March 15). Validation Report for the Operational Test Command Advanced Simulation and Instrumentation Systems (OASIS) Enterprise.

United States Army Test and Evaluation Command. (2009, August 11). Creation of Operational Environments and Technology Enterprises to Support Operational Testing.

United States House of Representatives. (2010, March 23). House Armed Services Committee Panel on Defense Acquisition Reform. Washington, DC.

Valerdi, R. (2009). A Prescriptive and Adaptive Testing Framework (PATFrame) for Unmanned and Autonomous System of Systems. Cambridge, MA: MIT.

Wiegers, E. (1999). First Things First: Prioritzing Requirements. *Software Development* , *7* (10), 24-30.

Womack, J.P. and D.T. Jones. (1996). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation.* New York, NY: Simon and Schuster.

Womack, J.P., D.T. Jones and D. Ross. (1990). *The Machine That Changed The World.* New York, NY: Harper Collins Publishers .

(THIS PAGE INTENTIALLY LEFT BLANK)

Appendix A – Technical Description for *PATFrame* (Valerdi et al. 2008)

The technology proposed is a decision support tool encompassing a prescriptive and adaptive framework for unmanned autonomous systems of systems UASoS Testing (*PATFrame*). *PATFrame* directly addresses BAA technical topic areas *TTE-6 Prescribed System of Systems Environments* and *MA-6 Adaptive Architectural Frameworks* and via two related tasks. These tasks will occur in parallel and will be gradually integrated during the technology development process. *PATFrame* will be implemented using a software dashboard that will enable improved decision making for the unmanned autonomous systems (UAS) T&E community. The technology addresses the Modeling & Architecture and Testbeds & Test Environments areas in the unmanned autonomous systems testing (UAST) capability framework.

Per the BAA instructions, the proposed technology is classified as Type I (New Technology) with a Technology Readiness Level of 3. It leverages existing basic principles from systems and software engineering (TRL 1) as well as preliminary research in frameworks, design idioms, causal models, and ontologies (TRL 2). The next step in the maturation process is to perform analytical studies to set *PATFrame* into an appropriate context. This validation exercise will be done across the five operational domains (ground, air, space, water, underwater) of interest to the T&E community. The development of *PATFrame* will occur via the following interrelated tasks:

Task #1: Prescribed System of Systems Environments

Guided by technical topic TTE-6, MIT will develop a prescriptive framework for System of Systems testing in the UAS domain. The framework will serve as a foundation for a new UAS T&E paradigm which will support UASoS verification, mission verification, as well as a performance measurement framework.

The objectives of the UAS T&E framework includes:

- Develop an understanding of the theoretically best SoS test strategies through a normative framework
- Determine the best in class test strategies available across industry and government through a descriptive framework

- Develop a prescriptive framework for improving decision making according to normative and descriptive standards

The relationships between these objectives are shown in Figure 31.

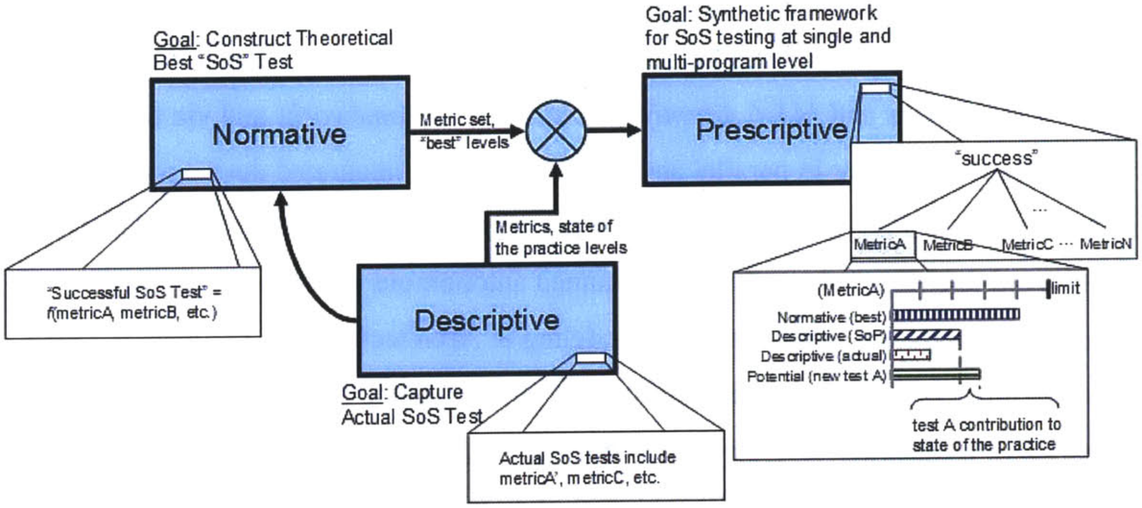


Figure 31 – Prescribed System of Systems Environments

Normative Framework

The purpose of the normative framework is to develop an understanding of the theoretically best SoS test strategies that are not constrained by policy, budgets, or time. This baseline provides an upper bound that can be used to compare the performance of other test strategies, technologies, or risk management approaches in the SoS T&E domain. The normative ideal also helps provide metrics for evaluating the adequacy of SoS testing.

Descriptive Framework

A descriptive framework helps determine the state of the practice test strategies available across industry and government given the current initiatives (i.e., JTAM) and tools (i.e., DoDAF). The descriptive aspect of SoS testing in the UAS arena is obtained through document review, interviews of transition partners, and analysis of current processes. The goal of capturing the actual way SoS T&E is done is to compare the state of the practice to the normative reference point using previously defined metrics.

Prescriptive Framework

The normative and descriptive reference points lead to the development of a prescriptive framework that improves decision making in SoS T&E at the single and multi-program level. At this stage, the marginal contributions of executing certain SoS tests or investing in specific UAS T&E technologies can be quantified.

The efforts being leveraged for Task 1 are research in: advanced systems engineering, frameworks, multi-attribute tradespace exploration, and system of systems engineering.

Because the framework is based on empirical data, it addresses several needs of the UAST T&E community that are generalizable across the ground, air, space, water, underwater domains through the ability to:

- Prioritize the tests to be performed on the SoS
- Perform tradeoffs to improve investment decisions on future test technologies
- Perform risk management analysis on the test program being implemented

Task #2: Adaptive Architectural Frameworks

Guided by technical topic MA-6, a joint team comprised of MIT, USC, and UTA will develop an adaptive architectural framework for System of Systems testing in the Unmanned & Autonomous Systems domain. The framework, which will fit within *PATFrame*, will provide the capability to predict when test systems need to adapt based on the emergent properties of UAS. The proposed framework will be an integration of ontologies, causal models, dynamic adaptation, effective design idioms, and decision making.

The objectives of the adaptive architectural framework include:

- Develop a UAS SoS test and evaluation ontology model
- Develop a causal model illustrating system dynamics relationships of SoS test and evaluation
- Develop effective design idioms for SoS architecture notions (i.e., components, connectors, events, etc.)
- Implement a framework for dynamic adaptation of system of systems
- Augment traditional DoDAF guidance to support UAS SoS test and evaluation and evolve towards capability-driven development

The relationships between these objectives are shown in Figure 32.

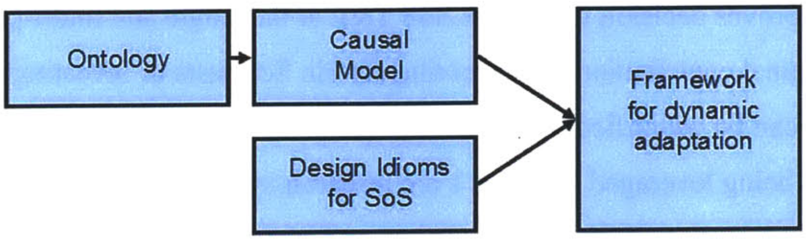


Figure 32 – Adaptive Architectural Framework

Ontology Model

An ontology can help with SoS testing by describing (1) objects and events (entities) in a domain, (2) relationships between objects and events, (3) use of objects and events inside and outside the boundary of the domain, and (4) rules that govern the entities' existence and behavior.

Development of an ontology provides a basis for those interested in the field of UAS T&E to understand the entities and relationships and terminology within the T&E domain. The ontology can provide a foundation common basis of understanding for UAS test and evaluation, and will be used in the support of other deliverables including the development of other deliverables for the adaptive architecture framework and prescriptive model.

Causal Model

System dynamics can be used for modeling the interaction and relationships between the components of a complex system. The system dynamics approach is based on cause-effect relationships seen in the system under study and includes principles of feedback control systems. When an element of a system indirectly influences itself, the portion of the system involved is called a feedback or causal loop. The most powerful feature of system dynamics is realized when multiple cause-effect relationships are connected and form a feedback loop relationship.

A causal map or model illustrates the combination of factors that can affect the test process and the positive and negative effect relationships between modeled factors. A causal map will help to facilitate an understanding of the complex behavioral feedback combinations expected with UAS SoS T&E and can represent a view of the associated complex system dynamics.

Design Idioms

We propose to develop system design idioms embodied in an SoS test architecture that can be effectively tied to test implementations and exploited in continuous system testing, runtime monitoring, and adaptation. This will enable highly modular and adaptable systems, but without a loss in test efficiency. The proposed solution will be unique in that it is envisioned to support both (traditional) system modeling and analysis as well as (novel) system implementation in terms of a framework directly supporting a core set of SoS architectural notions: components, connectors, communication ports, events, etc. Furthermore, each of these core constructs will be extensible, thus enabling engineers to exploit the specifics of a given application domain and testing context. We will endow our notations, techniques, and tools with a number of supporting capabilities that uniquely support rapid exploration of alternatives via analysis and simulation, and, in turn, quantifiable evaluation and selection of test choices.

Framework for Dynamic Adaptation

The ontology, causal model, and design idioms will be integrated into a framework for dynamic adaptation. This adaptable framework will be used as a foundation for both evaluating appropriate tests for a given SoS and suggesting modifications to the SoS in response to test results. To this end, we will employ a multi-dimensional system analysis and decision-making framework. This framework will be integrated with our ontology and causal model for dynamic adaptation support. It will allow continuous assessment of SoS architecture for critical properties that will facilitate decision making in the T&E area.

Augment DoDAF Guidance

While current DoDAF views can be used to understand the UAS architecture, there are no views specific to T&E. The team proposes the development of extensions to the current DoDAF set of views to support UAS SoS T&E. These extensions would require the definition of the test environment and architecture to support UAS and SoS test and evaluation. The development of the extension will help to provide a means to predict when a test system needs to adapt based on the framework for dynamic adaptation. Emergent behavior will provide potential triggers for various prioritized actions based on specific event types and monitored parameter inputs from ground, air, space, water, underwater systems.

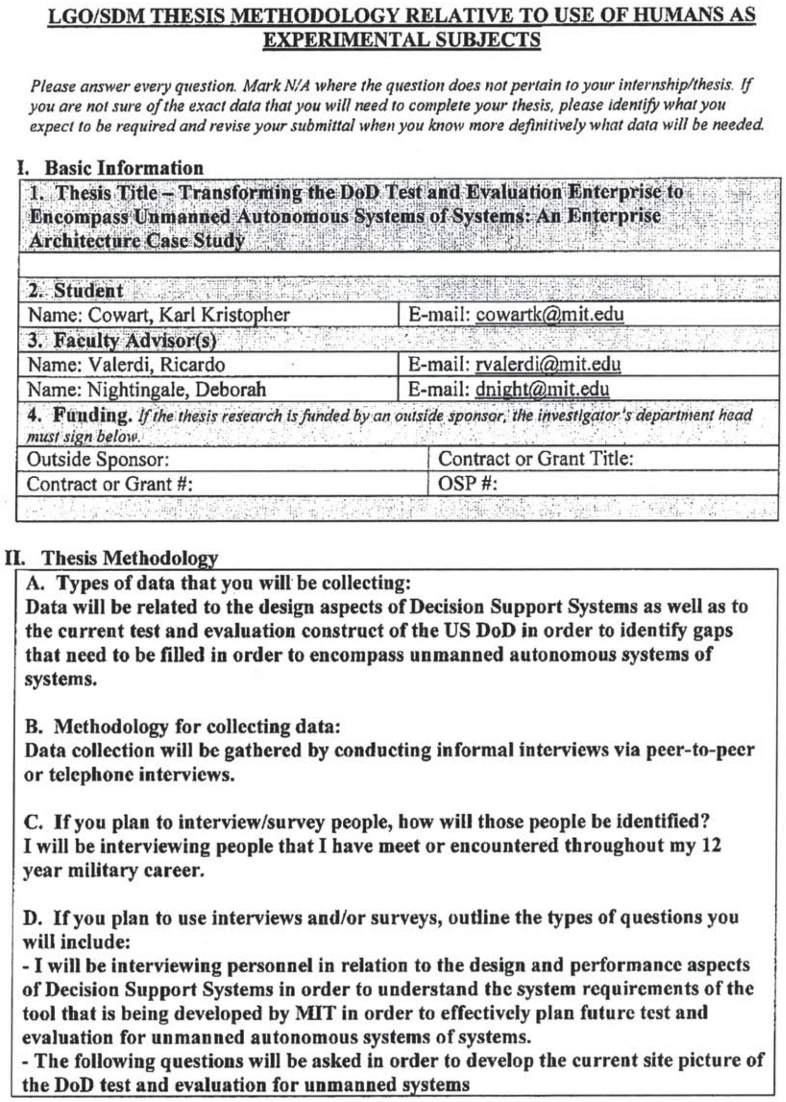
Because the framework is adaptable to emergent SoS properties, it addresses several needs for the UAST T&E community including the ability to:

- Have a common basis of understanding (common language) of UAS T&E through an ontology
- Facilitate an understanding of the complex behavioral feedback combinations expected with UAS SoS T&E
- Use design idioms for rapid exploration of alternatives for quantification of test choices
- Dynamically adapt test choices given emergent properties of the SoS

Augment existing tools such as DoDAF to enable improved communication and decision making

The synergies between the prescriptive (task #1) and adaptive (task #2) characteristics of this work motivate the integration of these concepts into a holistic decision support tool, *PATFrame*.

Appendix B – Couhes Form



LGO/SDM THESIS METHODOLOGY RELATIVE TO USE OF HUMANS AS EXPERIMENTAL SUBJECTS

Please answer every question. Mark N/A where the question does not pertain to your internship/thesis. If you are not sure of the exact data that you will need to complete your thesis, please identify what you expect to be required and revise your submittal when you know more definitively what data will be needed.

I. Basic Information

1. Thesis Title – Transforming the DoD Test and Evaluation Enterprise to Encompass Unmanned Autonomous Systems of Systems: An Enterprise Architecture Case Study	
2. Student	
Name: Cowart, Karl Kristopher	E-mail: cowartk@mit.edu
3. Faculty Advisor(s)	
Name: Valerdi, Ricardo	E-mail: rvalerdi@mit.edu
Name: Nightingale, Deborah	E-mail: dnight@mit.edu
4. Funding. *If the thesis research is funded by an outside sponsor, the investigator's department head must sign below.*	
Outside Sponsor:	Contract or Grant Title:
Contract or Grant #:	OSP #:

II. Thesis Methodology

A. Types of data that you will be collecting:
Data will be related to the design aspects of Decision Support Systems as well as to the current test and evaluation construct of the US DoD in order to identify gaps that need to be filled in order to encompass unmanned autonomous systems of systems.

B. Methodology for collecting data:
Data collection will be gathered by conducting informal interviews via peer-to-peer or telephone interviews.

C. If you plan to interview/survey people, how will those people be identified?
I will be interviewing people that I have meet or encountered throughout my 12 year military career.

D. If you plan to use interviews and/or surveys, outline the types of questions you will include:
- I will be interviewing personnel in relation to the design and performance aspects of Decision Support Systems in order to understand the system requirements of the tool that is being developed by MIT in order to effectively plan future test and evaluation for unmanned autonomous systems of systems.
- The following questions will be asked in order to develop the current site picture of the DoD test and evaluation for unmanned systems

- 1 -

1. **What do you as a stakeholder value in the current T&E enterprise from an unmanned systems perspective?**
2. **What strategic objectives do you see as relevant in today's T&E enterprise from an unmanned systems perspective?**
3. **In thinking about your stakeholder value and strategic objectives, what metrics and/or measures of performance do you utilize in evaluating unmanned systems?**
4. **What applied processes (attributes) do you use at the tactical level that helps your metrics / performance measures line up with your stakeholder value?**
5. **Where do you see unmanned systems applications 5 to 10 years from now?**

E. Location of the research:
The vast majority of the research will occur on campus here at MIT. A small amount of research will take place off campus as required (i.e., conference attendance or interviewee worksite)

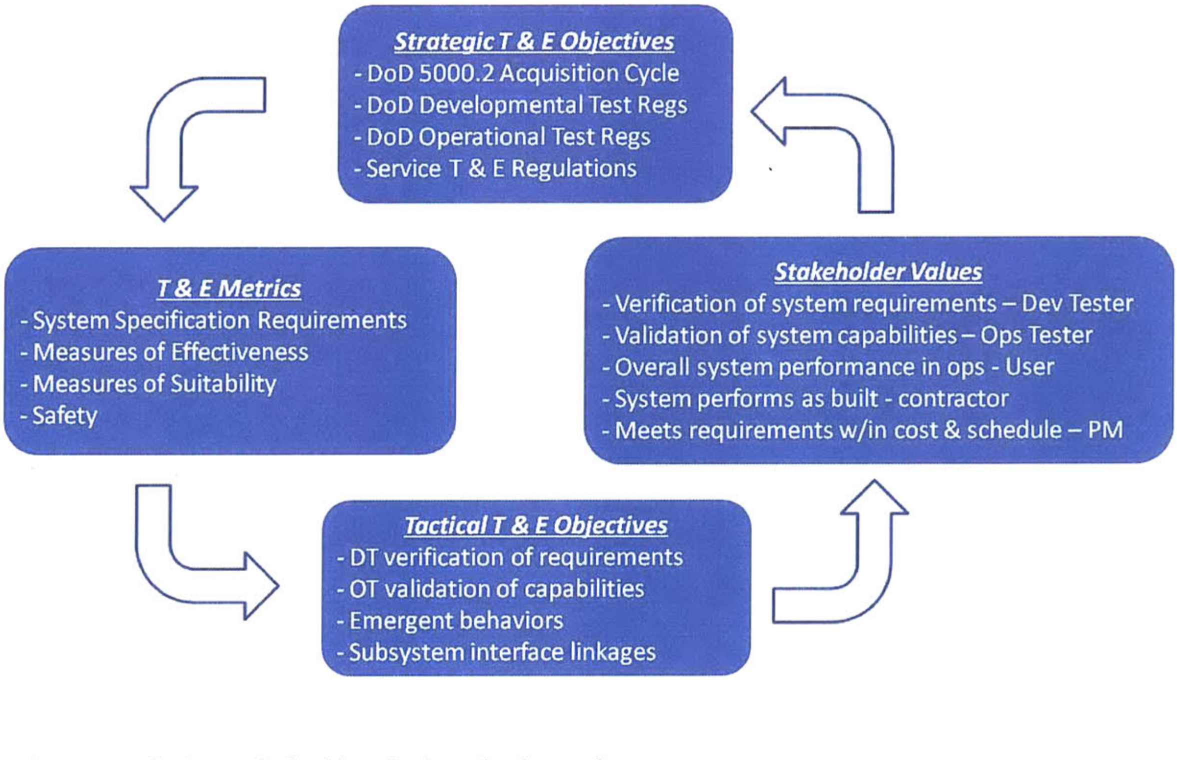
not KKC 2Aug2010

G. Procedures to ensure confidentiality:
Names of personnel interviewed will be released.

Signature ____________________ **Date** 8/2/2010
Director, SDM Fellows Program

Appendix C – Stakeholder Interview Framework

The figure below represents the framework that will be utilized to determine the alignment of the "As-Is" Test and Evaluation enterprise from the perspective of unmanned systems. The alignment analysis starts by identifying the Stakeholder Values for each of the stakeholders. This diagram shows the author's initial guess of the values for the T&E enterprise stakeholder's, which is based on the author's tacit knowledge from working as an Air Force acquisition professional for the past 12 years. The Stakeholder Values then link to the Strategic T&E Objectives, which are driven from the items shown in the diagram below. The Strategic T&E Objectives are then traced to the T&E Metrics utilized to determine the performance status for the testing that is underway. The T&E metrics then tie to the Tactical T&E Objectives of the system or system of systems that is being tested. Also, the Tactical T&E Objectives represent the attributes the enterprise uses in order to tie the T&E Metrics to the Stakeholder Values.



Questions to ask the stakeholder during the interview:

1. What do you as a stakeholder value in the current T&E enterprise from an unmanned systems perspective?
2. What strategic objectives do you see as relevant in today's T&E enterprise from an unmanned systems perspective?
3. In thinking about your stakeholder value and strategic objectives, what metrics and/or measures of performance do you utilize in evaluating unmanned systems?
4. What applied processes (attributes) do you use at the tactical level that helps your metrics / performance measures line up with your stakeholder value?
5. Where do you see unmanned systems applications 5 to 10 years from now?

Appendix D – Stakeholder Legitimacy Factors

Table 21 – Stakeholder Power Factor Determination (Grossi 2003)

Power Factor	Level description	Level Range
Coercive	The stakeholder threatening position to obtain the outcomes desired from the integrated enterprise is null or very low	0-2
	The stakeholder uses threatening arguments to obtain the outcomes it desires from the enterprise	2-4
	The stakeholder is able to pose real threats regarding his claims on the enterprise	4-6
	The stakeholder is capable of using some elements of force, violence, or restraint to obtain benefits from the enterprise	6-8
	The stakeholder is determined and totally capable of using force, violence, or any other resources to obtain desired outcome from the enterprise	8-10
	Coercive Power Level	
Utilitarian	The stakeholder has null or very low control over the resources (material, financial, services, or information) used by the enterprise	0-2
	The stakeholder has some control over some of the resources used by the enterprise	2-4
	The stakeholder controls the use of some of the resources used by the integrated enterprise	4-6
	The stakeholder heavily administers significant number of the resources used by the enterprise	6-8
	The stakeholder extensively administers most of the resources used by the enterprise	8-10
	Utilitarian Power Level	
Symbolic	The stakeholder does not use or barely uses normative symbols (prestige, esteem) or social symbols (love, friendship, acceptance to influence on the enterprise system	0-2
	The stakeholder uses some level of normative symbols or social symbols to influence on the enterprise	2-4
	The stakeholder uses moderate levels of normative symbols or social symbols to influence on the enterprise system	4-6
	The stakeholder relies on normative symbols and/or social symbols to claim his stakes from the enterprise system	6-8
	The stakeholder extensively uses normative symbols and social symbols in order to obtain value from the enterprise system	8-10
	Symbolic Power Level	
	Power Attribute (Weighted Average)	

Table 22 – Stakeholder Criticality Factor Determination (Grossi 2003)

Criticality Factor	Level description	Level Range
Urgency	The stakeholder is time insensible or has very low demands for a timely response to its claims at risk in the enterprise	0-2
	The stakeholder asks for its stakes or values with enough anticipation allowing the enterprise to attend them in a timely manner	2-4
	The stakeholder requires attention to its stakes in plausible or reasonable times	4-6
	The stakeholder calls for a prompt attention to the stakes at risk in the enterprise	6-8
	The stakeholder demands immediate attention to the stakes it compromise in the enterprise and their associated payoffs	8-10
	Urgency Level	
Importance	The stakeholder has null or very low dependency on the stakes it puts at risk in the enterprise	0-2
	The stakeholder shows low dependency on the values obtained from the enterprise	2-4
	The stakeholder relies on the values obtained from the enterprise for its future actions or operations	4-6
	The stakeholder shows high dependency on the stakes it contributes at risk in the enterprise	6-8
	The stakeholder demonstrates very high dependency on the stakes it puts at risk in the enterprise and on the values obtained from it	8-10
	Importance Level	
	Criticality Attribute (Weighted) Average	

Table 23 – Stakeholder Legitimacy Factor Determination (Grossi 2003)

Legitimacy Factor	Subtypes	Level Description	Level
Broad Definition		Generalized perception or assumption that the actions of a stakeholder are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions	0-10
Pragmatic	Exchange Legitimacy	Extent to which the stakeholder maintains a materialistic (based on goods, services, or any other type of exchange) relationship with the enterprise, and the importance of those exchanges to the welfare of the enterprise system	0-10
	Influence Legitimacy	Extent to which the stakeholder helps in defining the strategic or long-term interests of the whole enterprise and its submission to those interests before its own welfare	0-10
	Dispositional Legitimacy	Degree to which the stakeholder is predisposed to share or adopt the enterprise values demonstrating honesty, decency, and trustworthiness in the relationship	0-10
		Pragmatic Legitimacy Average Level	
Moral	Consequential Legitimacy	Degree to which the accomplishments of the stakeholder are perceived by the whole enterprise system as "the right thing to do"	0-10
	Procedural Legitimacy	Extent by which the stakeholder's value creation processes are perceived as sound and good efforts to achieve some, albeit invisible, ends as valued by the enterprise system	0-10
	Structural Legitimacy	The degree by which the stakeholder is perceived as having the right internal organizational structure to perform its assigned role in the enterprise system	0-10
	Personal Legitimacy	Extent by which the leaders of the stakeholder organization are perceived as having the adequate charismas, personalities, and authority to perform the job the stakeholder is supposed to do for the enterprise system	0-10
		Moral Legitimacy Average Level	
Cognitive	Comprehensibility Legitimacy	Degree of existence of cultural models that provide plausible explanations for the stakeholder participation in an enterprise and its relative endeavors	0-10
	Taken-for-grantedness Legitimacy	Degree to which the legitimacy of the stakeholder is taken for granted without an explicit evaluative support	0-10
		Cognitive Legitimacy Average Level	
		Legitimacy Attribute (Weighted) Average	

(THIS PAGE INTENTIALLY LEFT BLANK)

Appendix E – Systems vs Systems of Systems (Sauser 2006)

Element	*System*	*Systems of Systems*	*Cross References*
Autonomy	Autonomy is ceded by parts in order to grant autonomy to the system	Autonomy is exercised by constituent systems in order to fulfill the purpose of the SoS	*Directed* (Eisner, 1993), *Planned* (Eisner 1993, Lane and Valerdi 2005), *Embedded* (Keating, Rogers, et al. 2003), *Autonomy* (Monarch and Wessel 2005, Keating, Rogers,et al. 2003, Bar-Yam 2004, SoSECE Sep 2003)
Belonging	Parts are akin to family members; they did not choose themselves but came from parents. Belonging of parts is in the nature.	Constituent systems choose to belong on a cost/benefits basis; also in order to cause greater fulfillment of own purposes, and because of belief in the SoS supra purpose.	*Enterprise* (Carlock and Fenton 2001, Lane and Valerdi 2005, SoSECE 9 Nov 2005), *Shared Mission* (Holland, 1995, Shenhar, 2001, Crossley, 31 Mar 2004), *Sharing* (Lane and Valerdi 2005)
Connectivity	Prescient design, along with parts, with high connectivity hidden in elements, and minimum connectivity among major subsystems.	Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possibly via a netcentric architecture, to enhance SoS capability.	*Interdependence* (Cook 2001, Eisner, Marciniak and McMillan 1991), *Distributed* (DeLaurentis 2005, Eisner 1993, Keating, Rogers, et al. 2003, Lane and Valerdi 2005, Sage and Cuppan 2001, Shenhar 2001, Maier 1998), *Networked* (Lane and Valerdi 2005, Shenhar 2001, DeLaurentis 2005), *Multiple Solutions* (Eisner, Marciniak and McMillan 1991), *Loose Coupling* (Monarch and Wesse, 2005), *Integration* (Luskasik 1998, Maier 1998, Pei 2000), *Interoperability* (Pei 2000, Manthorpe Jr 1996, Carney, Fisher and Place 2005), *Synergism* (Manthorpe Jr 1996, Bar-Yam 2004)
Diversity	Managed i.e. reduced or minimized by modular hierarchy; parts' diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of belonging, the hierarchy	Increased diversity in SoS capability achieved by released autonomy, committed belonging and open connectivity	*Independence* (Crossley 31 Mar 2004, DeLaurentis 2005, Eisner, Marciniak and McMillan 1991, Maier 1998, Sage and Cuppan 2001), *Diversity* (Keating, Rogers, et al. 2003, Crossley 31 Mar 2004, Sage 2003), *Heterogeneous* (DeLaurentis 2005, Purdue 2005)
Emergence	Foreseen, both good and bad behavior, and designed in or tested out as appropriate	Enhanced by deliberately not being foreseen, though its crucial importance is, and by creating an emergence capability climate that will support early detection and elimination of bad behaviors.	*Evolving* (Cook 2001, DeLaurentis 2005, Lane and Valerdi 2005, Luskasik 1998, Monarch and Wessel 2005, Sage and Cuppan 2001, Maier 1998), *Intelligence* (Lane and Valerdi 2005), *Sum is Greater than Parts* (Eisner, Marciniak and McMillan 1991), *Behaviors* (Parks, Jung and Ramotowski 2004), *Emergence* (DeLaurentis 2005, Lane and Valerdi 2005, Monarch and Wessel 2005, Sage and Cuppan 2001, Maier 1998, Bar-Yam 2004), *Dynamic* (Lane and Valerdi 2005), *Adaptive* (Carney, Fisher and Place 2005, SoSECE 9 Nov 2005)

(THIS PAGE INTENTIONALLY LEFT BLANK)

Appendix F – Acronyms

ADM – Acquisition Decision Memorandum
AFB – Air Force Base
AFMC – Air Force Materiel Command
AFOTEC – Air Force Operational Test and Evaluation Center
AFROC – Air Force Requirements Oversight Council
ALFUS – Autonomous Levels of Unmanned Systems
AT&L – Acquisitions, Technology and Logistics
CAC – Contextual Autonomous Capability
CDD – Capabilities Development Document
CDR – Critical Design Review
COA – Certificate of Authority
COP – Community of Practice
COTS – Commercial Off the Shelf
CPD – Capabilities Production Document
DAG – Defense Acquisition Guide
DDR&E – Director of Developmental Research and Engineering
DDT&E – Director of Developmental Test and Evaluation
DoD – Department of Defense
DOT&E – Director of Test and Evaluation
DT – Developmental Testing
DSS – Decision Support System(s)
EA – Enterprise Architecture
EC – Environmental Complexity
EMD – Engineering and Manufacturing Design
ESD – Engineering Systems Division
FAA – Federal Aviation Authority
HI – Human Independent
HPT – High Performance Team
IDT/OT – Integrated Developmental Test and Operational Test
JCIDS – Joint Capabilities Integration and Development System
JROC – Joint Requirements Oversight Council
LCMP – Life Cycle Management Plan
LSI – Lead Systems Integrator
LRIP – Low Rate Initial Production
MC – Mission Complexity
MIT – Massachusetts Institute of Technology
NAS – National Air Space

NIST – National Institute of Standards and Technology
OT – Operational Testing
PDR – Preliminary Design Review
PRR – Production Readiness Review
R&D – Research and Development
SAF – Secretary of the Air Force
SCMPD – System Capability and Manufacturing Process Demonstration
SoS – Systems of Systems
SoSE – Systems of Systems Engineering
SVR – System Verification Review
TIPT – Test Integrated Product Team
T&E – Test and Evaluation
TRMC – Test Resource and Management Center
UAS – Unmanned Autonomous Systems
UAST – Unmanned Autonomous Systems Test
UASoS – Unmanned Autonomous Systems of Systems
UAV – Unmanned Aerospace Vehicle
UMS – Unmanned System
US – United States
USAF – United States Air Force
USAFE – United States Air Forces Europe
USIR – Unmanned Systems Roadmap